

5

Organic Chemistry

“Syncrude Canada was just about to begin operating its oil sands plant when I was graduating. I had attended several talks about the oil sands, so my primary reason for interviewing with the company was to see their pilot plants. When they offered me a job, however, I accepted. One of the advantages of working in such a large company is that I have had the opportunity to carry out research in numerous areas. I like the variety of the work.

When I joined the work force, I was concerned whether I had the correct qualifications for the job. I have since learned that my formal training was really just the beginning of my learning. What I learned in school is how to approach a problem. On the job, I’ve expanded my knowledge and learned how to work in diverse teams to solve our problems.”



Jean Cooley,
Research Associate,
Syncrude Canada

As you progress through the unit, think about these focusing questions:

- What are the common organic compounds and what is the system for naming them?
- How does society use the reactions of organic compounds?
- How can society ensure that the technological applications of organic chemistry are assessed to ensure future quality of life and a sustainable environment?





GENERAL OUTCOMES

In this unit, you will

- explore organic compounds as a common form of matter
- describe chemical reactions of organic compounds

Prerequisites

Concepts

- atomic structure
- physical and chemical properties of molecular compounds
- covalent bonding
- polar and nonpolar molecules
- intermolecular forces

Skills

- drawing diagrams and writing formulas of molecules
- building molecular models
- conducting and analyzing diagnostic tests
- describing safety and disposal

You can review prerequisite concepts and skills in the Chemistry Review unit, on the Nelson Web site, and in the Appendices.

A Unit Pre-Test is also available online.

www.science.nelson.com



Knowledge

1. According to Lewis' theory, the number of bonding electrons in an atom determines the number of bonds the atom will form. Complete **Table 1** for five elements that are often involved in organic compounds.

Table 1 Atomic Structures of Some Common Nonmetals

Element	Atomic number	Number of electrons	Number of valence electrons	Lewis symbol	Number of bonding electrons
carbon					
hydrogen					
oxygen					
nitrogen					
sulfur					

2. Different formulas for molecules can be used to predict the types of intermolecular bonding that exist in a substance. Complete **Table 2** for some common compounds of carbon.

Table 2 Some Common Carbon Compounds

IUPAC name	Molecular formula	Lewis formula	Structural formula	Types of intermolecular forces
	CH ₄ (g)			
dichloromethane	CH ₂ Cl ₂ (l)			
methanol				
methyl amine	CH ₃ NH ₂ (l)			
ethane				
ethene	C ₂ H ₄ (g)			
ethyne		H : C :: C : H	H — C ≡ C — H	
	C ₂ H ₅ OH(l)			
ethyl mercaptan	C ₂ H ₅ SH(l)			

3. Use VSEPR theory to predict the shapes of each of the following molecules. Predict whether each molecule is polar or nonpolar.
 - (a) chloromethane, CH₃Cl(g), used as a refrigerant
 - (b) carbon dioxide, CO₂(g), produced by hydrocarbon combustion
 - (c) formaldehyde, HCHO(g), used as a disinfectant
 - (d) ethyne, C₂H₂(g), used as a fuel for welding
 - (e) ethene, C₂H₄(g), used to make plastics
4. The octane used in automobile fuel is considered nonrenewable because it is produced from petroleum, a fossil fuel. Ethanol is considered a renewable fuel since it can be produced from biomass, such as grain.
 - (a) Write a balanced chemical equation for the combustion of octane, C₈H₁₈(l).
 - (b) Write a balanced chemical equation for the combustion of ethanol, C₂H₅OH(l).
 - (c) Describe some diagnostic tests for the reaction products in (a) and (b).

5. Photosynthesis is the formation of carbohydrates and oxygen from carbon dioxide, water, and sunlight, catalyzed by chlorophyll in the green parts of a plant (**Figure 1**).
- Write a balanced chemical equation for photosynthesis, using $\text{C}_6\text{H}_{12}\text{O}_6(\text{aq})$ for the carbohydrate.
 - During summer in the Northern Hemisphere, the level of carbon dioxide in the atmosphere decreases slightly. Use the chemical equation in (a) to explain this phenomenon.

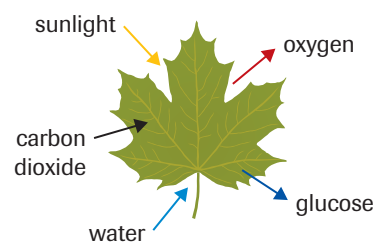


Figure 1
Photosynthesis consumes carbon dioxide and produces oxygen.

Skills

6. Boiling point is a measure of the strength of the intermolecular forces in a substance. There is evidence to suggest that London forces exist among all molecules in the liquid or solid state. Chemists explain the strength of London forces as being dependent on the number of electrons in the molecule. Polar molecules exert relatively weak dipole–dipole forces in addition to London forces. Molecules with OH, NH, or FH groups have relatively strong hydrogen bonds in addition to London forces. The purpose of this activity is to test the ability of the theoretical concepts of London forces, dipole–dipole forces, and hydrogen bonding to predict the relative boiling points of three families of compounds. Complete the Prediction, Analysis, and Evaluation (2, 3) of the investigation report.

Problem

What are the trends in boiling point for three families of carbon compounds?

Design

The boiling points of twelve organic compounds (from three chemical families) are measured experimentally. The boiling point evidence is used to test the Prediction. The polarity of the molecules and the hydrogen bonding are controlled variables within each family of compounds.

Evidence

Table 3 Boiling Points of Three Families of Carbon Compounds

Hydrocarbon	Boiling point (°C)	Organic halide	Boiling point (°C)	Alcohol	Boiling point (°C)
$\text{CH}_4(\text{g})$	–164	$\text{CH}_3\text{Cl}(\text{g})$	–24	$\text{CH}_3\text{OH}(\text{l})$	65
$\text{C}_2\text{H}_6(\text{g})$	–89	$\text{C}_2\text{H}_5\text{Cl}(\text{g})$	12	$\text{C}_2\text{H}_5\text{OH}(\text{l})$	78
$\text{C}_3\text{H}_8(\text{g})$	–42	$\text{C}_3\text{H}_7\text{Cl}(\text{l})$	47	$\text{C}_3\text{H}_7\text{OH}(\text{l})$	97
$\text{C}_4\text{H}_{10}(\text{g})$	–0.5	$\text{C}_4\text{H}_9\text{Cl}(\text{l})$	78	$\text{C}_4\text{H}_9\text{OH}(\text{l})$	117

7. Liquid hydrocarbons are readily flammable and often evaporate easily to form explosive mixtures with air.
- What WHMIS symbol is found on a container of a liquid hydrocarbon?
 - Outline the precautions that must be taken when working with liquid hydrocarbons.
 - Describe an acceptable method for handling waste flammable liquids.

Hydrocarbons from Petroleum

► In this chapter

-  Exploration: Burning Fossil Fuels
-  Investigation 9.1: Classifying Fossil Fuels
-  Case Study: Fossil Fuel Industries in Alberta
-  Web Activity: Coal in Alberta
-  Explore an Issue: Coalbed Methane
-  Investigation 9.2: Structures and Properties of Isomers
-  Web Activity: West Nile Denial
-  Lab Exercise 9.A: Chemical Properties of Aliphatics and Aromatics
-  Lab Exercise 9.B: Boiling Points of Sample Aliphatics and Aromatics
-  Investigation 9.3: Fractional Distillation (Demonstration)
-  Web Activity: Karl Chuang
-  Case Study: Octane Number
-  Investigation 9.4: Bitumen from Oil Sands
-  Investigation 9.5: Solvent Extraction
-  Case Study: The Athabasca Oil Sands
-  Investigation 9.6: Complete and Incomplete Combustion

The most widely accepted explanation of the origin of fossil fuels is that they come from decaying plant and animal material. The carbon cycle is a model connecting the organic reactions of photosynthesis, digestion, and respiration (**Figure 1**). The formation of fossil fuels can be seen as the end of the natural processes in the carbon cycle and the beginning of the technological processes described in this chapter.

Humans have invented methods to extract fossil fuels from below the surface of Earth. We mostly burn fossil fuels to produce heat and useful energy. These combustion reactions produce carbon dioxide, which feeds back into the carbon cycle.

Recently, we have developed many other technological uses of fossil fuels. We now produce vast quantities of petrochemicals (chemicals created from fossil fuels), most of which are not meant to be burned. Petrochemicals include methanol (windshield antifreeze), ethylene glycol (radiator antifreeze), chlorofluorocarbons (CFCs: refrigerator and air conditioner coolants), plastics (polyethylene and polyvinylchloride (PVC)), and pesticides. In this chapter, you will learn about the extraction and refining of fossil fuels. In the next chapter, you will learn about the use of fossil fuels to create petrochemicals. For both uses, fossil fuels are a very valuable nonrenewable resource. The impact of fossil fuel use on our lives and our planet is everywhere around us.

Historically, natural resources were seen as assets to be developed, and it was usual to imagine technological solutions to problems. In recent times, however, we have come to realize that technology is limited in its ability to cope with resource depletion and pollution. Many people, including scientists, believe we need to move toward an Aboriginal viewpoint that sees natural resources as gifts to be treasured for future generations. In order to save our planet from irreparable harm, we have a responsibility to live in harmony with nature for the mutual benefit of nature and humanity.



STARTING Points

Answer these questions as best you can with your current knowledge. Then, using the concepts and skills you have learned, you will revise your answers at the end of the chapter.

1. What are the origins and sources of fossil fuels?
2. How are fossil fuels extracted and refined?
3. What are the main hydrocarbon families, and how do they differ?
4. What are some uses of fossil fuels and their components?



Career Connections:
Petroleum Engineer; The Petroleum Industry

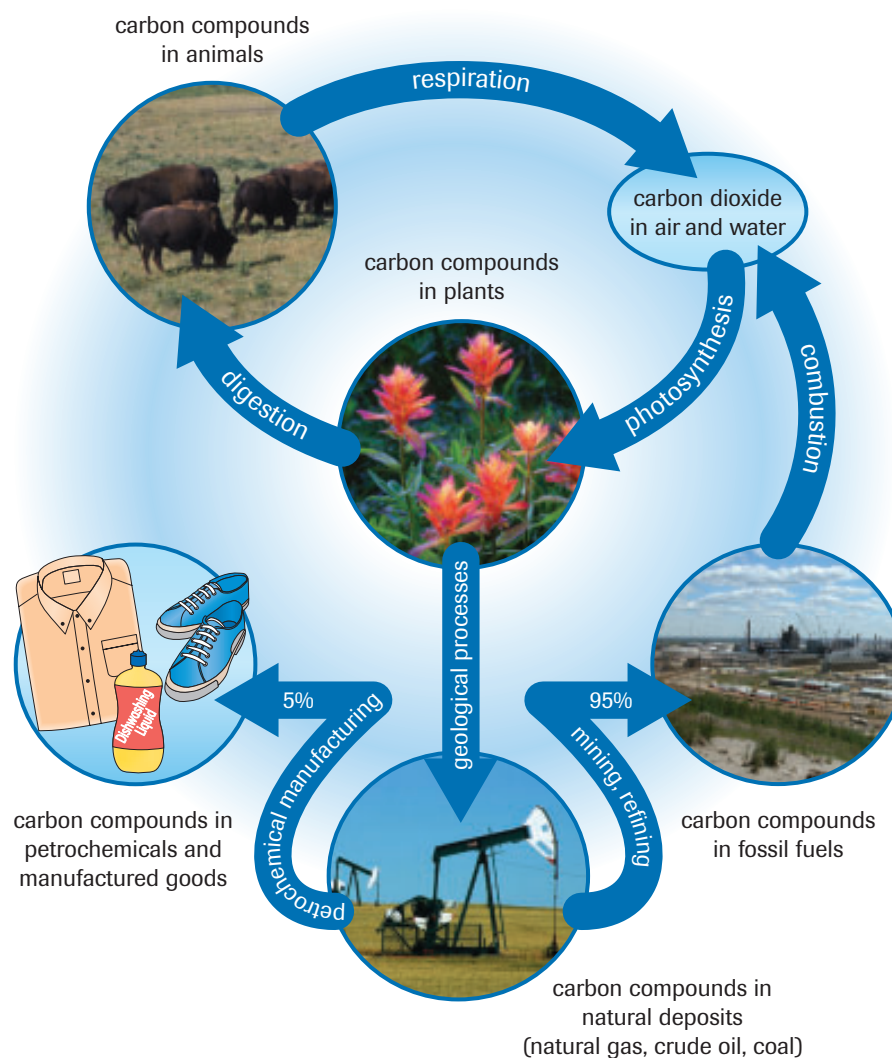


Figure 1

The carbon cycle is an illustration of the interrelationship of all living things with the environment and with technologies that refine and use fossil fuels.

► **Exploration** *Burning Fossil Fuels*

Scientists agree that fossil fuels are a nonrenewable, finite resource. Fossil fuels in Alberta include coal, natural gas, crude oil, oil sands, and heavy oil. Studies have indicated that about 95% of the fossil fuels used in Alberta is used for energy production, including natural gas and propane for home heating, and gasoline and diesel fuel for cars, trucks, and buses. The evidence indicates that about 5% of fossil fuels is converted into petrochemicals (such as plastics) through technologies based on chemical reactions. Two issues related to burning fossil fuels for energy production are

- whether we should be burning a very valuable resource at the current rate
- whether we should be saving more of this resource for petrochemical use in the future

Investigate the first of these issues as you work through Chapter 9, and the second issue in Chapter 10.

Issue Checklist

- | | | |
|----------------------------------|---|---|
| ☐ Issue | ☒ Design | ☒ Analysis |
| ☐ Resolution | ☒ Evidence | ☒ Evaluation |

Resolution: The burning of fossil fuels for heat and transportation should be significantly reduced.

While progressing through Chapter 9, complete the Design, Evidence, Analysis, and Evaluation components of the first issue report.

Governments, industry, and citizens alike speak of sustainable development. The United Nations Commission on Environment and Development defines sustainable development as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. Keep this concept in mind while completing this unit-long exploration.

9.1 Fossil Fuels

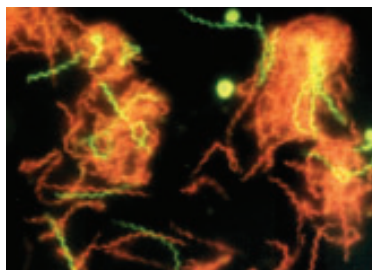


Figure 1

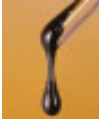
Extremophiles are microorganisms that thrive in harsh environments, such as boiling water, acid, rocks, the coolant of a nuclear reactor, and toxic wastes. Identification of these carbon-based organisms raises the hopes of astrobiologists that basic life forms may exist on moons and planets in the universe. On Earth, the study of organic chemistry began with living things. Beyond Earth, scientists look for evidence of living things.

Life as we know it is based on carbon chemistry (**Figure 1**). Therefore, it is not surprising that the early definition of organic chemistry was related to compounds obtained only from living things. Today, **organic chemistry** is a major branch of chemistry that deals with compounds of carbon, excluding oxides (such as CO(g)) and ionic compounds of carbon-based ions such as carbonate, cyanide, and carbide ions, for example, $\text{Na}_2\text{CO}_3\text{(s)}$, NaCN(s) , and $\text{CaC}_2\text{(s)}$, respectively. In spite of this broader definition, the major source of carbon compounds is still living or previously living things, such as plants, animals, and all types of fossil fuels.

Coal, oil sands, heavy oil, crude oil, and natural gas are nonrenewable sources of fossil fuels. They are also the primary sources of **hydrocarbons**—compounds containing carbon atoms bonded to hydrogen atoms. Hydrocarbons are the starting points in the synthesis of thousands of products, including specific fuels, plastics, and synthetic fibres. Some hydrocarbons are obtained directly by physically refining oil and natural gas (both called petroleum), whereas others come from further (chemical) refining (**Table 1**).

Refining is the technology that includes physical and chemical processes for separating complex mixtures into simpler mixtures or near-pure components. The refining of coal and natural gas involves physical processes; for example, coal may be crushed. Components of natural gas are separated either by solvent extraction or by condensation and distillation. Oil sands refining involves a chemically enhanced physical process followed by the complex refining of the bitumen/tar. Crude oil refining is more complex than coal or gas refining, but many more products are obtained from crude oil.

Table 1 Refining of Fossil Fuels—a Preview

Fossil fuel ¹	Extraction	Physical processing ²	Chemical processing	Sample uses
Natural gas ³ 	natural pressure underground	condensation and distillation	removal of hydrogen sulfide and carbon dioxide at a gas plant	heating buildings; source of ethane, propane, and butane
Coalbed methane 	water removed from underground, if necessary	removal and disposal of saline water, if necessary	removal of non-combustibles at a gas plant	same as natural gas, including production of hydrogen and methanol
Crude oil 	water or gas injection underground	water, sand, and salt removal, and fractional distillation in a tower	hydrocracking and catalytic reforming	gasoline, jet fuel, and asphalt
Heavy oil 	steam injection underground	separation from water and solids; fractional distillation	heavy oil hydrocracking and catalytic reforming	same as crude oil
Oil sands (bitumen) 	physical mining and in situ steam or hot water injection	hot water extraction and floatation; centrifugation; fractional distillation	coking, hydrocracking, hydrotreating	synthetic crude used as crude oil
Coal 	surface and underground mines	sorting, crushing, and/or grinding	none or gasification for alternative delivery	energy for producing electricity

1. These Alberta fossil fuels are listed in order of increasing density. 2. In many cases, physical processing also includes removing water and solid contaminants from the raw material. 3. For natural gas, the chemical processing precedes the physical processing.



INVESTIGATION 9.1 Introduction

Classifying Fossil Fuels

Alberta has many different fossil fuels. Samples of fossil fuels can be described and classified in terms of their physical properties of colour, transparency, viscosity, and density. In this investigation, the focus is on density.

Purpose

The purpose of this investigation is to use the known properties of fossil fuels to analyze the provided samples.

Problem

What are the classes of the fossil fuel samples provided?

To perform this investigation, turn to page 401.

Report Checklist

- | | | |
|----------------------------------|--|--|
| ☐ Purpose | ☐ Design | ☒ Analysis |
| ☐ Problem | ☐ Materials | ☒ Evaluation (1, 3) |
| ☐ Hypothesis | ☒ Procedure | |
| ☐ Prediction | ☒ Evidence | |

Design

Equal-volume samples of fossil fuels are provided in sealed containers of equal mass. The mass of each sample, including the container, is determined. The fossil fuel samples are classified based on their densities.



Case Study

Fossil Fuel Industries in Alberta

Alberta is very rich in fossil fuels. The most widely accepted hypothesis for the origin of these fossil fuels is that they formed from sand, silt, and plant and animal remains starting about 500 Ma ago. The majority of hydrocarbons found in Canada exist in the Western Canada Sedimentary Basin, which covers all but the northeast corner of Alberta (**Figure 2**).

Coal, oil sands, heavy oil, crude oil, natural gas, and coalbed methane are fossil fuels found in significant quantities in Alberta. From a technological perspective, each of these fuels has historically had to go through several cycles of discovery, research, and development.

Discovery, Research, and Development

Discovery has occurred throughout history, from Aboriginal peoples discovering oil sands along the banks of the Athabasca River and farmers digging fence-post holes and finding coal, to today's sonar equipment used for conducting underground seismic surveys. Research and development (R & D) has historically been conducted separately and sequentially: research by universities and development by industry. However, this model of R & D has changed and continues to change, with more overlap of the roles of universities and industries. For example, on a small scale, government (the Alberta Research Council) scientists did research and development on the hot-water process for extracting oil from the oil sands. Industry and engineers then ran larger-scale tests and developed the sophisticated technologies required for economical world-scale plants. Researchers continue the R & D cycle in their attempts to extract oil from deep oil sands and depleted oil wells.

Petroleum Discoveries

Natural gas was first discovered by chance near Medicine Hat, Alberta, in 1883. The drillers were looking for water, and found a methane-rich flammable gas. The discovery, and the many subsequent fires, prompted author Rudyard Kipling to refer to

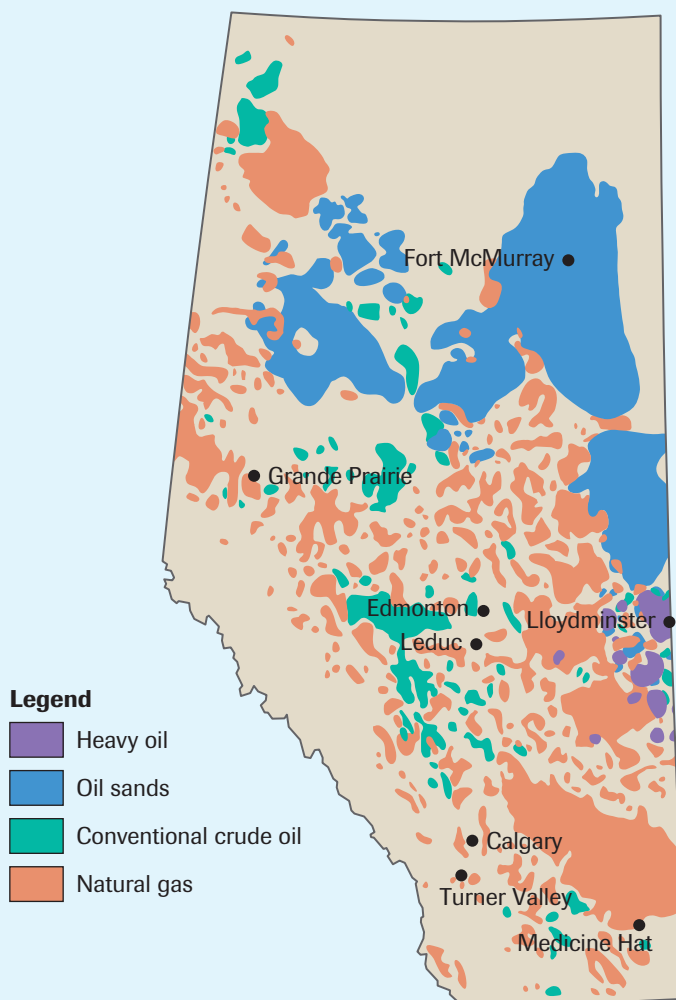


Figure 2
Fossil fuels in Alberta

Medicine Hat as Hell's Kitchen. The plentiful gas made Medicine Hat famous for natural gas street lights and pottery furnaces. Natural gas was then discovered in Cessford, Turner Valley, Suffield, Bow Island, and Viking, Alberta.

Hell's Half Acre was the nickname for Turner Valley, Alberta, where oil was discovered in 1914 and in 1936—beneath the natural gas. The next important discovery of crude oil was Leduc 1 on February 13, 1947 (**Figure 3**). This gusher near Devon, south of Edmonton, started an oil rush. Oil was struck in the Devonian Formation after Imperial Oil had drilled 133 unsuccessful wells. Perseverance, it appears, is just as important for technologists as it is for scientists (and students).

The largest oil field in Canada is the Pembina field, near Drayton Valley, Alberta. Geologists continue to search for oil and gas in the sedimentary basin to Rainbow Lake, Norman Wells, and the Beaufort Sea. Much of the exploration in Alberta today is to find coalbed methane gas and oil sands (see the Explore an Issue on page 365 and the Case Study on page 395). The search for crude oil also continues.



Figure 3
Leduc 1

Infrastructure

With the discovery and production of oil and natural gas came the need for infrastructure: oil and gas pipelines, gas plants, and oil refineries. Pipelines are needed to transport the oil or gas to a refinery, to local consumers, and to national and international consumers. These pipelines criss-cross Alberta—as evidenced by cut-lines and road-crossing signs. Pipelines were, and continue to be, built to eastern Canada, the west coast, and the United States.

Oil refineries were first built in 1923 and 1939 in Calgary. As the discovery of oil moved northward, so did the refineries. As the size of the discoveries grew, so did the size of the refineries. Refineries continue to be built, especially for the refining of bitumen (from oil sands) and heavy oil. The refining of natural gas in Alberta requires over 800 gas plants to remove impurities (such as hydrogen sulfide) and to extract the valuable components from the gas (including ethane, propane, and butane).

Social and Environmental Challenges

The advantages to Albertans of the large quantities of fossil fuels found in Alberta are numerous. Major examples include using gasoline (from crude oil) to propel our cars and trucks, using natural gas to heat our homes, and using coal to produce our electricity. In general, the fossil fuel industry in Alberta has important effects on our economy and our lifestyles.

Our fortune of fossil fuels also presents challenges. Some of these challenges include the effects on communities and infrastructure. For example, in fast-growing communities close to fossil fuel extraction and refining plants, there is a higher

probability of a shortage of housing and social services. Rapid and extensive development of resources also presents environmental challenges. For example, the extraction and refining of many fossil fuels requires water. The extraction process disturbs surface land and air, and creates water pollution to varying degrees.

There are nearly always trade-offs (a negative for a positive result) when we decide to develop a natural resource. Research and technological fixes can only solve so many problems. The demands (needs and wants) of society and of individuals may be justified in our minds, but we also need to consider the potential negative consequences of our everyday actions.

Case Study Questions

- (a) Based upon Figure 2 on the previous page, which are the most widespread fossil fuel deposits in Alberta?
(b) What fossil fuels found in Alberta are not depicted in Figure 2?
- (a) What is the classical relationship between research and development?
(b) Which group of people performed each of the R & D?
- What technological infrastructure is necessary for processing and transporting fossil fuels?
- Give an example of a trade-off between a positive and a negative consequence of fossil fuel production.

Extension

- Research and report alternative hypotheses to the currently accepted hypothesis for the formation of fossil fuels, such as the organic and the inorganic hypotheses.

www.science.nelson.com



- In what general regions of Alberta have we found
(a) oil sands, heavy oil, crude oil, and natural gas?
(b) coal and coalbed methane?
(c) significant wind, solar, biomass, and geothermal energy production?

www.science.nelson.com



- Research when and where natural gas was discovered in Canada's Northwest Territories.

www.science.nelson.com



- Continue your research on the Resolution in the Exploration on page 357: The burning of fossil fuels for heat and transportation should be significantly reduced. Gather statements, pro and con, from a variety of perspectives. Focus on the effects of the discovery and extraction of fossil fuels in Alberta.

www.science.nelson.com





Case Study—Coal in Alberta

Research indicates that the most abundant fossil fuel reserve in Alberta and Canada is coal. To help describe coal, scientists have classified it into four broad classes based upon the percentage of carbon. From highest carbon content to lowest, the classes of coal are anthracite, bituminous, sub-bituminous, and lignite. You will find out more about coal as you pursue this Case Study.

www.science.nelson.com



Could the Athabasca Tar Sands Catch Fire?

The tar sands, or oil sands, are rich in fossil fuels. So could a huge fire spread through the vast deposits? Listen to a University of Calgary professor's answer to find out.

www.science.nelson.com



Section 9.1 Questions

- Classify the following chemicals as organic or inorganic.

(a) $\text{CaCO}_3(\text{s})$	(e) $\text{CH}_3\text{COOH}(\text{l})$
(b) $\text{C}_{25}\text{H}_{52}(\text{s})$	(f) $\text{CO}_2(\text{g})$
(c) $\text{CaC}_2(\text{s})$	(g) $\text{KCN}(\text{s})$
(d) $\text{CCl}_4(\text{l})$	(h) $\text{C}_{12}\text{H}_{22}\text{O}_{11}(\text{s})$
- List six different types of fossil fuels found in Alberta.
- All fossil fuels require some refining after being extracted from the ground. State the two major kinds of refining and describe how, in general, they are different.
- Write molecular and structural formula equations for the combustion of the following hydrocarbon components of natural gas. Assume complete combustion.
 - lighting a butane lighter, $\text{C}_4\text{H}_{10}(\text{g})$
 - burning pentane, $\text{C}_5\text{H}_{12}(\text{l})$, in winter gasoline
- The carbon dioxide gas produced by combustion of hydrocarbons enters the atmosphere.
 - What change can the carbon dioxide induce on the climate? Explain briefly.
 - Write an equation to represent the production of an acid component of acid rain from carbon dioxide.
- Classify the following statements as pro or con to the Resolution in the Exploration on page 357. Also classify the perspective from which the statement is made.
 - Research is being done to reduce or reuse carbon dioxide emissions.
 - Alternative energy sources, such as wind and solar power, may reduce energy-use effects on the environment.
 - Industries producing ethanol from grain should receive the same tax breaks as industries producing synthetic crude oil from oil sands.
 - The yields of crude oil from wells and of synthetic crude from oil sands are increasing due to better and better equipment and techniques.
 - Votes can be gained by accelerating the extraction of crude oil and of coalbed methane from available deposits.
 - The laws governing the extraction of fossil fuels by energy companies need to be more stringently enforced.
 - Developing our fossil fuel resources is the morally right thing to do—it helps people.
 - Communities depend on the energy industries for supporting their families and way of life.
- What kinds of energy sources do you use in your home and from what fossil fuels do they come?
- List three renewable sources of energy naturally available in Alberta.
- What kinds of jobs are available working on oil and gas drilling rigs? Look at the options and choose an occupation on or around the rigs. Describe the job, its requirements, and the recommended salary. Where would you go to train for this job?

www.science.nelson.com



9.2 Alkanes from Natural Gas

Natural gas is removed from underground by drilling a deep hole into the ground where geologists have predicted that natural gas and/or oil is to be found. Nature makes the geologists' task of predicting the presence of oil and gas very challenging, as illustrated in **Figure 1**, but modern technologies provide increased certainty to their predictions. From a chemistry perspective, the separation of the rock and water from the oil and gas can be explained by solubility theory. For example, nonpolar substances (such as oil) do not dissolve in polar substances (such as water). Some ionic substances (such as limestone) are only slightly soluble in water, and no ionic substances dissolve in oil.

Some common types of traps for oil and gas

1. Limestone reef trap of the type found in Leduc and Redwater.
2. Reservoirs in folded and faulted strata. Turner Valley's oil was found in traps like this.
3. Stratigraphic trap of the type found in southeast Saskatchewan.
4. Displacement of rock layers along a fault. This type of structure is found in some areas of the Peace River district.

Legend

	Sandstone
	Limestone
	Shale
	Gas
	Oil
	Water

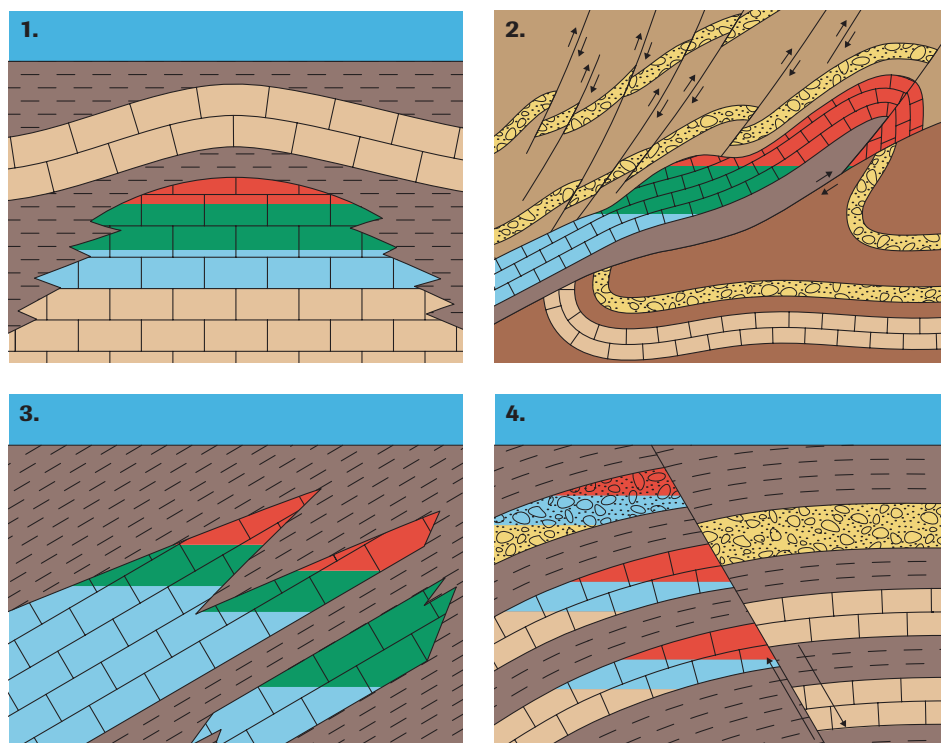


Figure 1

Trapping of natural gas and crude oil in geological formations (limestone and sandstone)

Natural gas has varying composition but it is primarily methane, $\text{CH}_4(\text{g})$ (**Table 1**). Methane is the smallest of the alkane molecules. An *alkane* is a class of hydrocarbons that contains only single bonds and only carbon and hydrogen atoms. In this section, first you will learn about the natural occurrence and the technological extraction and refining of natural gas. Then you will learn about the chemical and physical properties of alkanes. Finally, you will investigate the theoretical structure and nomenclature of this important class of hydrocarbons.

Raw natural gas often contains impurities that make it “sour.” This means that it contains the very toxic gas hydrogen sulfide, which forms acidic solutions when mixed with water. The hydrogen sulfide gas (also called rotten-egg gas) presents a major safety problem for gas-field workers. Exposure to only a small quantity of this gas is deadly. Fortunately, the human nose is extremely sensitive to hydrogen sulfide gas—an early warning system.

DID YOU KNOW?

Smelly Additives

Mercaptans are added to natural gas and to propane. Natural gas and propane are odourless, which makes them difficult to detect and a potential explosion hazard. Mercaptans, however, have a very strong odour. The addition makes gas leaks much more noticeable, and, therefore, much safer.

Natural Gas Refining

Raw natural gas is piped from the well site to one of more than 800 gas treatment plants in Alberta. At the plant, water and liquid hydrocarbons are removed from the gas before it is chemically refined in an absorber tower. During this technological process, the sour natural gas reacts with an amine such as aqueous diethanolamine, $(\text{C}_2\text{H}_4\text{OH})_2\text{NH}(\text{aq})$, under relatively high pressure and low temperature. The amine “sweetens” the gas by removing any hydrogen sulfide (H_2S) and carbon dioxide gases, which are then released from the amine in a regenerator tower. The hydrogen sulfide then partially reacts with oxygen to produce sulfur dioxide. The mixture is then sent to a sulfur recovery unit containing Claus converters (**Figure 2**). The Claus converters convert the H_2S and SO_2 mixture to elemental sulfur and water vapour. You may have seen large yellow blocks of sulfur beside gas plants in Alberta (**Figure 3**). Natural gas may range from 0% to 80% hydrogen sulfide. Sweet natural gas directly from a well contains no hydrogen sulfide but still needs to have water, liquid hydrocarbons, and carbon dioxide removed before being pumped into a natural gas pipeline.

Sweet natural gas (natural or refined) is a mixture of hydrocarbons (**Table 1**). The composition of natural gas depends on the region of the province and the specific well within the region from which it comes. Some industries may preferentially purchase gas with the composition that best suits them, such as high percentages of propane to sell to customers.

Table 1 Typical Composition of Sweet Natural Gas

Component	Chemical formula	Mole fraction (~%)	Boiling point (°C)
nitrogen	$\text{N}_2(\text{g})$	2.7	-196
carbon dioxide	$\text{CO}_2(\text{g})$	0.3	-78
methane	$\text{CH}_4(\text{g})$	83.6	-162
ethane	$\text{C}_2\text{H}_6(\text{g})$	11.6	-89
propane	$\text{C}_3\text{H}_8(\text{g})$	1.75	-42
butane	$\text{C}_4\text{H}_{10}(\text{g})$	0.15	-0.5
pentanes*	$\text{C}_5\text{H}_{12}(\text{l/g})$	0.08	vary (e.g., ~36)
hexanes*	$\text{C}_6\text{H}_{14}(\text{l/g})$	0.07	vary (e.g., ~69)

* Pentanes and hexanes are liquids under normal room conditions, but are vapour components of natural gas (just like water is a vapour component of air).

Although some of the natural gas may be burned directly or exported as a mixture of gases, most of the natural gas consumed in Alberta is further refined into separate components. At these refining (fractional distillation) plants, a simplified description is that the natural gas is cooled under high pressure to condense all the components except the methane gas. The condensed (liquid) portion is then slowly distilled to separate out the ethane, propane, butane, and pentane fractions (**Figure 4**). Some of the uses of these fractions are presented in **Table 2**.

Table 2 Uses of Natural Gas Components

Component	Some uses for the component
methane, $\text{CH}_4(\text{g})$	heating homes, fueling taxis, producing hydrogen and methanol
ethane, $\text{C}_2\text{H}_6(\text{g})$	cracked into ethene for producing many petrochemicals
propane, $\text{C}_3\text{H}_8(\text{g})$	heating homes and vacation trailers; fueling barbecues and stoves
pentane, $\text{C}_5\text{H}_{12}(\text{l/g})$	winter additive to gasoline for greater vaporization



Figure 2

An upgraded sulfur recovery unit was installed at Shell's Burnt Timber sour gas processing plant, 117 km northwest of Calgary, in the early 1990s. This facility processes natural gas from seven different gas fields that contain 0–28% hydrogen sulfide.



Figure 3

This photo shows a block of sulfur at the Caroline-Shantz sulfur-forming facility near Sundre, Alberta. Only about 60 out of 800 gas plants recover sulfur. Most gas plants process sweet (non-sulfur) natural gas.



Figure 4

Fractionation of natural gas provides a supply of propane.

DID YOU KNOW?

Helium From Natural Gas

Air ships used before and during the First World War were filled with explosive hydrogen gas. Looking for a safer alternative, Canadian John McLennan invented a method for extracting the tiny quantities of helium from natural gas. McLennan designed and built a plant in Calgary during the First World War to provide helium for safer air ships for the Allies.

DID YOU KNOW?

Pipelines and Gas Processing Plants

Crude oil, synthetic crude, diluted bitumen, natural gas, ethane, and other pipelines criss-cross Alberta and Canada. Many farm fields in Alberta have one or more pipeline(s) under the ground. Is there a pipeline or a gas processing plant near you?

www.science.nelson.com



+ EXTENSION

CBC radio ONE

QUIRKS & QUARKS

Mining Methane

In a fuel-hungry world, geologists and researchers are searching everywhere for new resources. The Mallik 2002 drilling program explored buried deposits of methane in Canada's Arctic, and has raised hopes that these resources might be financially viable. There could be as much fuel here as in the entire world's reserves of traditional fossil fuels.

www.science.nelson.com



Practice

- Describe the two main stages in the refining of most natural gas. Identify which changes are physical and which are chemical.
- Draw structural formulas for the first four members of the alkanes. Show all atoms and bonds.
- Chemists have determined the boiling point of the components of natural gas (see Table 1 on the previous page).
 - What is the trend in boiling point as the number of carbon atoms increases for the alkane family?
 - Explain any trend that you identify that relates the size of an alkane molecule to its boiling point.
- Geologists are able to use various technologies to empirically determine the geological features of oil- and gas-containing formations (Figure 1). Use intermolecular force and solubility theories to help explain the separation of
 - water and crude oil
 - limestone (assume $\text{CaCO}_3(\text{s})$) and crude oil
 - crude oil and natural gas
- Chemical engineers indicate that hydrocarbon gases, such as methane ($\text{CH}_4(\text{g})$), evaporate from or are easily boiled off from crude oil.
 - Use what you know about solubility to explain the presence of methane in crude oil.
 - Use what you know about crude-oil-containing geological formations to create a hypothesis as to how the methane may have gotten into the crude oil.
- There is an increasing use of natural gas and a decreasing use of petroleum in Canada (Figure 5).

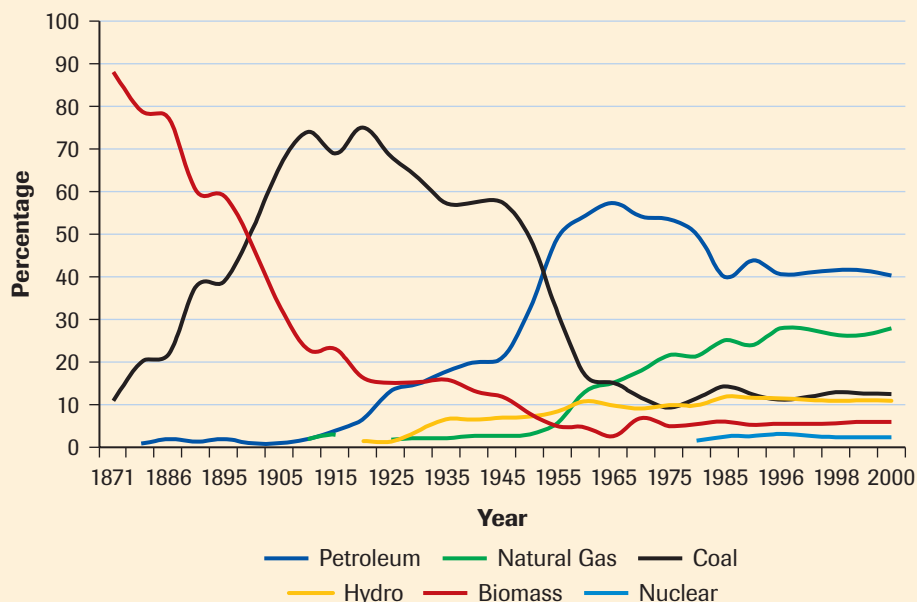


Figure 5
Energy use in Canada since 1871

- Suggest some reasons for the changes in use of natural gas and petroleum in Canada.
- Revisit your work on the Exploration: Burning Fossil Fuels at the beginning of this chapter. Add some of the statements from this section of study to your perspectives sheet relating to the resolution that the burning of fossil fuels should be decreased.

EXPLORE an issue

Coalbed Methane

Coal miners have known about coalbed methane for centuries. Sudden releases of methane underground have killed hundreds of miners by suffocation or explosions. Similar gas releases have even been the subject of hypotheses to explain strange happenings in the Bermuda Triangle (see Chapter 4, Figure 2, page 185). Productively controlling the release of methane from coal beds is a developing technology in Alberta. Coalbed methane has been described as the oil sands of natural gas. Alberta geologists have mapped a potentially huge resource for coalbed methane (**Figure 6**). The methane is held underground by the surrounding pressure of trapped water. Releasing that pressure releases the methane. The method of extraction involves drilling a well to the methane-rich coal seam and, in many cases, pumping the water out (**Figure 7**). Removing the water releases the pressure on the methane and the low-pressure methane flows to the surface. A (potentially noisy) compressor at the surface pumps the methane along a pipeline to a natural gas refining site. Recall that natural gas is mainly methane. Coalbed methane is a natural gas that comes from underground coal beds. This



Figure 6
Zones with coalbed methane potential in Alberta

Issue Checklist

- | | | |
|----------------------------------|---|---|
| ☐ Issue | ☐ Design | ☒ Analysis |
| ☐ Resolution | ☒ Evidence | ☒ Evaluation |

coalbed natural gas has a very high percentage of methane, hence its name. The water removed from the coalbed is typically saline (salty) and is placed in holding ponds until it can be pumped back down the well.

Unlike natural gas wells, where only a couple of wells are needed to recover the gas on an owner's land, up to eight coalbed methane wells may be needed on a section of land. The landowners are paid for leasing the land to the natural gas company. Landowners do not, typically, own the mineral rights to the methane underground. They only own the surface rights.

Issue

Accessing coalbed methane may present challenges with land, noise, and water.

Resolution

Coalbed methane extraction in Alberta should be stopped until further research has been conducted.

Design

Research, from a variety of perspectives, the pros and cons of coalbed methane extraction in Alberta.

www.science.nelson.com

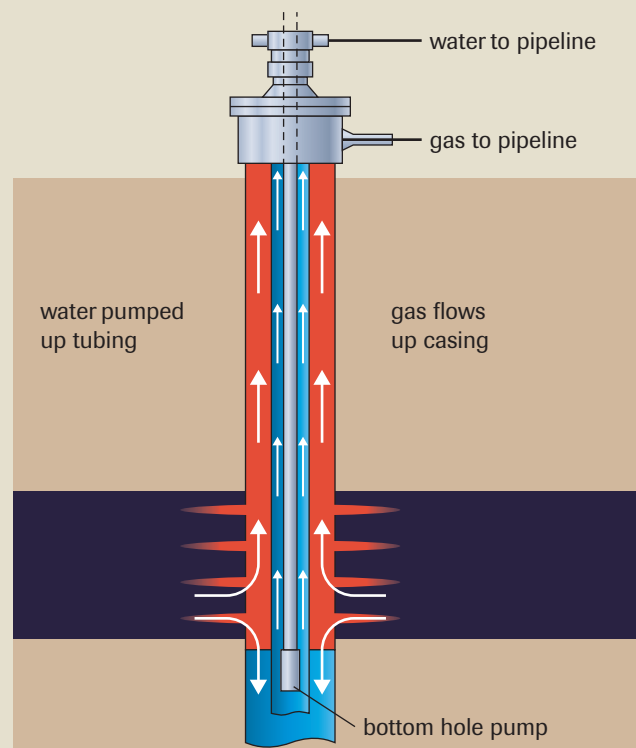


Figure 7
Coalbed methane extraction

Table 3 The Alkane Family of Organic Compounds

IUPAC Name	Formula
methane	$\text{CH}_4(\text{g})$
ethane	$\text{C}_2\text{H}_6(\text{g})$
propane	$\text{C}_3\text{H}_8(\text{g})$
butane	$\text{C}_4\text{H}_{10}(\text{g})$
pentane	$\text{C}_5\text{H}_{12}(\text{l})$
hexane	$\text{C}_6\text{H}_{14}(\text{l})$
heptane	$\text{C}_7\text{H}_{16}(\text{l})$
octane	$\text{C}_8\text{H}_{18}(\text{l})$
nonane	$\text{C}_9\text{H}_{20}(\text{l})$
decane	$\text{C}_{10}\text{H}_{22}(\text{l})$
-ane	$\text{C}_n\text{H}_{2n+2}$

Learning Tip

Memorize the prefixes indicating one to ten carbon atoms. See Table 3.

Naming Alkanes

Although hydrocarbons can be classified according to empirical properties, a more common classification is based upon the chemical formulas of the compounds. Hydrocarbons whose empirically determined molecular formulas indicate that the carbon-to-carbon bonds are only single bonds are called **alkanes**. The simplest member of the alkane series is methane, $\text{CH}_4(\text{g})$, which is the main constituent of the natural gas sold for home heating. The molecular formulas of the smallest alkanes (the first six of which are all typical constituents of natural gas) are shown in **Table 3**. Each formula in the series has one more CH_2 group than the one preceding it. Derived from empirically determined formulas and from bonding capacity, the general molecular formula for all alkanes is $\text{C}_n\text{H}_{2n+2}$; that is, a series of CH_2 units plus two terminal hydrogen atoms.

Alkanes are an example of what chemists call a **homologous series**—a sequence of molecules with similar structure and differing only the number of repeating units; e.g., CH_2 . Chemists also classify alkanes as **saturated hydrocarbons**—compounds of carbon and hydrogen containing only carbon–carbon single bonds with the maximum number of hydrogen atoms bound to each carbon.

The first syllable in the name of an alkane is a prefix that indicates the number of carbon atoms in the molecule (**Figure 8**). The prefixes shown in **Table 3** are used in naming all organic compounds.

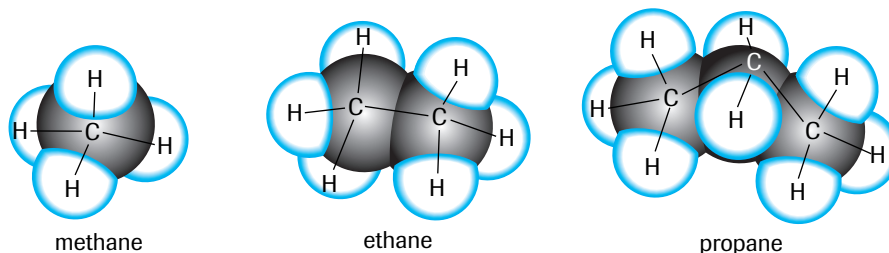
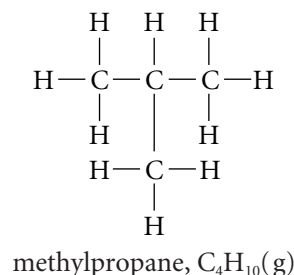
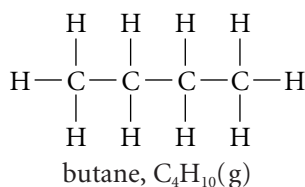


Figure 8 

The prefix *meth*– indicates one carbon atom, *eth*– signifies two carbon atoms, and *prop*– signifies three carbon atoms. The ending *–ane* indicates a chain of carbon atoms with single bonds only.

Structural Isomers

Chemical formulas, such as the ones in Table 3, tell you the total number of each kind of atom in a molecule. Except for the three smallest molecules (**Figure 8**), there are several structures that can have the same molecular formula. For example, C_4H_{10} has two different structural formulas, both satisfying the rules for chemical bonding.



So, while we can say that butane always has the formula, C_4H_{10} , we cannot say that a compound with the formula C_4H_{10} is always butane.

Compounds with the same molecular formula, but with different structures, are called **structural isomers**. Chemists created this theoretical concept to explain why isomers (different compounds with the same molecular formula) could have different physical and

chemical properties. Compounds with the same molecular formula but different properties must be differentiated in some way. For this reason, the two structures for C_4H_{10} shown above must have different names to avoid confusion. (See the next subsection.)

As the number of carbon atoms in a hydrocarbon increases, the number of possible isomers increases dramatically. For example, $C_{10}H_{22}$ has 75 possible isomers, $C_{20}H_{42}$ has 366 319, and $C_{30}H_{62}$ has 4 111 846 763 possible isomers. No wonder there are more compounds of carbon than compounds of all other elements combined!

Names and Structures of Branched Alkanes

The name of the compound indicates whether there are branches on a carbon chain. Prefixes (as in Table 3) identify groups of atoms that form branches on the structures of larger molecules. A *branch* is any group of atoms that is not part of the main structure of the molecule. For example, a branch consisting of only singly bonded carbon and hydrogen atoms is called an **alkyl branch**. In the names of alkyl branches, the prefixes are followed by a *-yl* suffix (Table 4). For example, consider the three isomers of C_5H_{12} shown in Figure 9. The unbranched isomer on the left is named pentane.

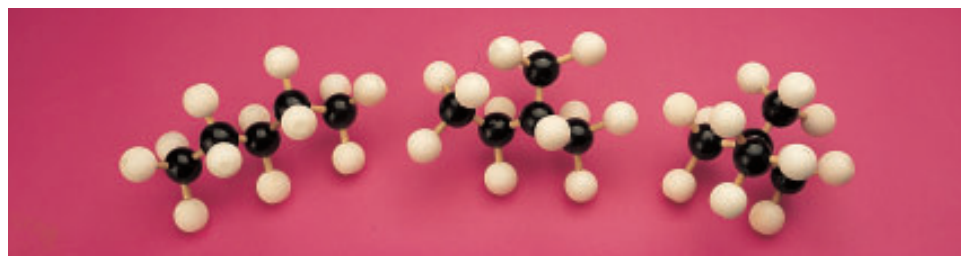
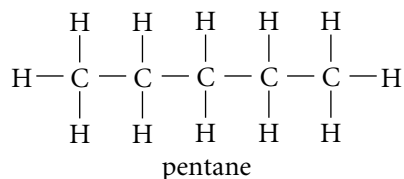


Figure 9

Each of the three isomers of C_5H_{12} has different physical and chemical properties.

The “straight” chain description of C_5H_{12} is shown below. Of course, there is a tetrahedral arrangement of bonds around each carbon atom, which produces the “saw-tooth” chain of carbon atoms modelled in Figure 9.



In the second isomer, there is a continuous chain of four carbon atoms with a methyl group on the second carbon atom. To name this structure, identify the *parent chain* — the longest continuous chain of carbon atoms. Here, the four carbons indicate that the parent chain is butane. Since a methyl group is added as a branch to the longest continuous chain of four carbon atoms, this isomer is called methylbutane. The same name applies when the methyl group replaces any of the four hydrogen atoms on the middle two carbon atoms of butane.

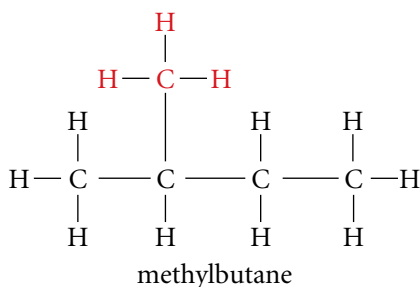


Table 4 Examples of Alkyl Branches

Branch	Name
$-CH_3$	methyl
$-C_2H_5$ ($-CH_2CH_3$)	ethyl
$-C_3H_7$ ($-CH_2CH_2CH_3$)	propyl

Learning Tip

Computer models of molecules can be displayed as

- wireframe (line structural)
- sticks (structural)
- ball and stick (structural)
- space filling

Interact with some of the alkane models at the following Web link.

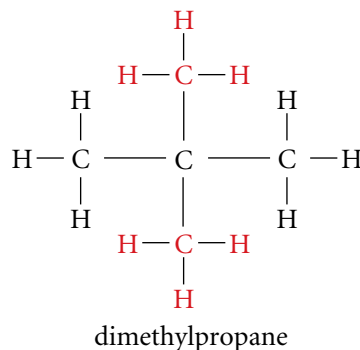
www.science.nelson.com



Learning Tip

To decide whether two different-looking structural formulas are the same molecule, rotate the structure top to bottom or left to right. If, by rotating the molecule, you can make it the same as another molecule, then it is the same molecule and has the same name (and is not a different isomer).

In the third isomer of C_5H_{12} in Figure 9, two methyl groups are attached to a three-carbon (propane) parent chain. This third pentane isomer is named dimethylpropane. There is no other isomer of dimethylpropane. Attaching one of the two methyl groups to an end carbon makes the molecule methylbutane. Attaching a methyl group to each end of propane makes the molecule pentane. See Figure 9.



Since there is only one methylbutane isomer and only one dimethylpropane isomer, we usually do not use numbers in the names of these molecules: 2-methylbutane and 2,2-dimethylpropane are acceptable but not necessary. In most cases, however, we need to number the carbon atoms to indicate the position(s) of branch(es) (substitution group(s)). In these cases, follow the steps below to name the branched hydrocarbon.

Learning Tip

Although IUPAC allows for alkyl groups (or any other atoms or groups of atoms substituted for hydrogen) to be placed in alphabetical order *or* in order of complexity (least to greatest), this textbook uses the rule of alphabetical order, for example, 3-ethyl-2,2-dimethylhexane. (Ignore the “di” and pay attention only to the “e” of ethyl and the “m” of methyl.)

SUMMARY Naming Branched Alkanes

Step 1: Identify the longest continuous chain of carbon atoms—the parent chain—in the structural formula. Number the carbon atoms, starting from the end closest to the branch(es), so that the numbers are the lowest possible.

Step 2: Identify any branches and their location number on the parent chain.

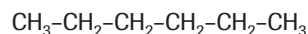
Step 3: Write the complete IUPAC name, following this format:
(number of location) – (branch name)(parent chain).

When writing the name of the alkane, list the branches in alphabetical order, ignoring, for example, the di- and tri- prefixes.

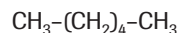
Learning Tip

Structural formulas show all bonds between atoms. This system is not efficient, especially for C–H bonds. Thus, the diagram is often simplified by not showing the bonds with H atoms, as shown in Sample Problem 9.1.

Long-chain hydrocarbons such as



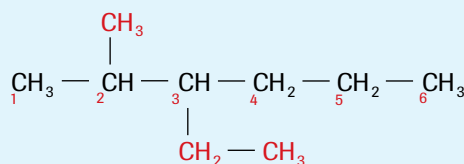
can be represented as



Both of these formulas and the one in Sample Problem 9.1 are condensed structural formulas.

► SAMPLE problem 9.1

Write the IUPAC name corresponding to the following condensed structural formula for a component of gasoline:



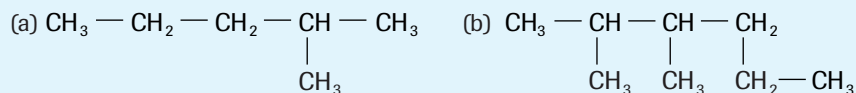
Step 1: The longest continuous chain has six carbon atoms. Therefore, the name of the parent chain is hexane.

Step 2: There is a methyl group branch at the second carbon atom, and an ethyl group branch at the third carbon atom of the parent chain.

Step 3: With the branches named in alphabetical order, the compound is 3-ethyl-2-methylhexane.

► COMMUNICATION example 1

Write the names from the condensed structural formulas for the following components of gasoline. The second component (b) is an isomer of octane.



Solution

(a) 2-methylpentane

(b) 2,3-dimethylhexane

A structural formula can illustrate an IUPAC name. For example, in the Communication Example above, 2,3-dimethylhexane has a hexane parent chain consisting of six carbon atoms joined by single covalent bonds. “2,3-dimethyl” tells us that there is a methyl group attached to the second carbon and another attached to the third carbon.

Above you have learned to name a branch-chained hydrocarbon when given the structural formula. The reverse process is to draw a structural formula when given the name. Both of these processes emphasize the conventions of communication agreed upon worldwide. These conventions are necessary for chemists to communicate their research in internationally distributed scientific journals and for health providers, for example, to administer the correct medication.

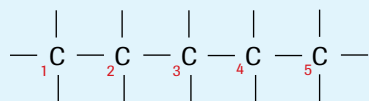
SUMMARY

Drawing Branched Alkane Structural Formulas

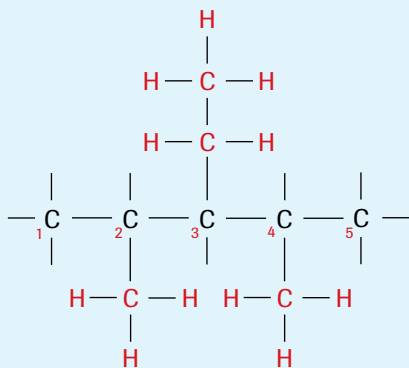
- Step 1: Draw a straight chain containing the number of carbon atoms represented by the name of the parent chain, and number the carbon atoms from left to right.
 Step 2: Attach all branches to their numbered locations on the parent chain.
 Step 3: Add enough hydrogen atoms to show that each carbon has four single bonds.

► SAMPLE problem 9.2

Draw a structural formula for 3-ethyl-2,4-dimethylpentane—possible component of gasoline.



Numbering this straight chain from left to right establishes the location of the branches. An ethyl branch is attached to the third carbon atom and a methyl branch is attached to each of the second and fourth carbon atoms.



Learning Tip

Be careful when choosing the longest continuous chain (parent chain) because the structure may twist and turn. If your name ends up with an alkyl branch on the number 1 position, then you have made a mistake in identifying the parent chain. For example, 1,1-dimethylpropane is incorrect and should be 2-methylbutane.

Learning Tip

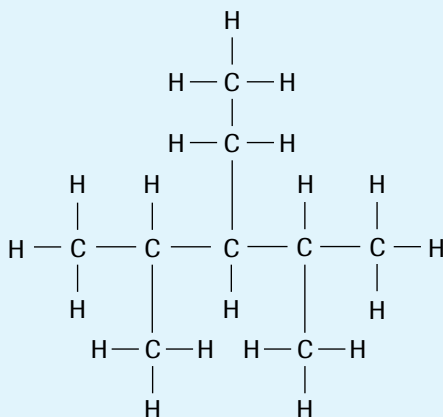
A molecular formula of an organic compound is not very useful because many isomers are often possible. To more clearly specify a particular compound, the structure needs to be indicated either by the IUPAC name or by a diagram. Chemists have invented many different kinds of diagrams to show the structure of a molecule. For our purposes, the structural formula (either full or condensed) is the most useful.

Because structure is so important to the physical and chemical properties of organic molecules, chemists make extensive use of molecular models such as space-filling models (Figure 8) and ball-and-stick models (Figure 9). Just as there are many other kinds of diagrams, there is also a variety of molecular models.

For a little more practice naming alkanes, follow the electronic link.

www.science.nelson.com 

In the following structural formula, hydrogen atoms are shown at any of the four bonds around each carbon atom that are left after the branches have been located.



COMMUNICATION example 2



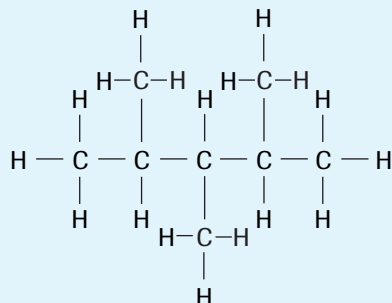
There are many different hydrocarbon molecules in gasoline, including many isomers. Draw the structural formula for the first isomer and the condensed structural formula for the second isomer of octane.

(a) 2,3,4-trimethylpentane

(b) tetramethylbutane

Solution

(a)



(b)

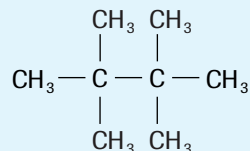


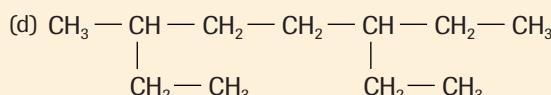
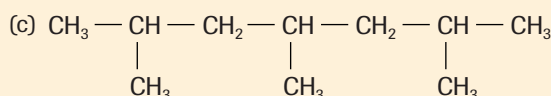
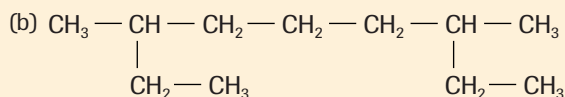
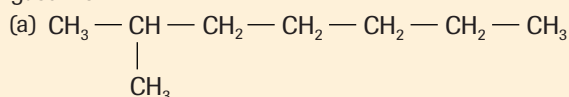
Figure 10

There are many different hydrocarbon mixtures that can be found at hardware stores.

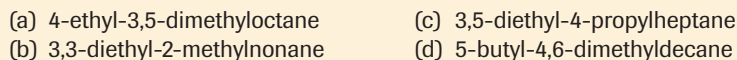
Practice

- Draw the structural formula of each alkane found in crude oil.
 - 2-methylpentane
 - 3-methylpentane
 - 2-methylhexane
 - 3-methylhexane
 - 3,4-dimethylhexane
 - 3-ethyl-2-methylhexane
 - 3,3-dimethylpentane
 - 2,5-dimethyl-4-propyloctane
- There are many different naphtha mixtures. Petroleum naphtha, commonly used as a camping fuel, is a mixture of alkanes with 5 or 6 carbon atoms per molecule (**Figure 10**).
 - Draw structural formulas and write the IUPAC names for all the isomers of C_6H_{14} .
 - Why are these isomers highly soluble in each other?

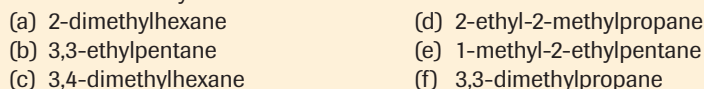
9. Automotive gasoline is a mixture that is largely composed of alkanes containing 5 to 12 carbon atoms per molecule. Write IUPAC names for the following components of gasoline:



10. Kerosene, used as a fuel for diesel and jet engines, contains alkanes with 12 to 16 carbon atoms per molecule. Draw structural formulas for the following components of kerosene:



11. IUPAC tries to standardize chemical communication throughout the world. For each of the following names, determine if it is a correct name for an organic compound. Give reasons for your answer and include a correct name.



DID YOU KNOW?

Chewing Gum

American Aboriginal peoples introduced Europeans to chewing spruce gum, which the Europeans quickly commercialized. In the 1950s, paraffin wax, a solid alkane, became the base for chewing gum. Today, more than one thousand varieties of gum are manufactured using various synthetic materials to replace natural gum ingredients.

Learning Tip

When naming hydrocarbons, not only must the branches be put in alphabetical order but also the set of numbers must be the lowest set. The lowest set of numbers is defined by IUPAC as being the set that starts with the lowest number; e.g., 2, 4 and 5 are lower than 3, 3 and 4. Start numbering the longest continuous chain from the end of the molecule with the closest branch.

Cycloalkanes

On the evidence of empirical formulas and chemical properties, chemists believe that organic carbon compounds sometimes take the form of cyclic hydrocarbons—hydrocarbons with a closed ring. When all the carbon–carbon bonds in a cyclic hydrocarbon are single bonds, the compound is called a **cycloalkane** (C_nH_{2n}).

Cycloalkanes are named by placing the prefix *cyclo* in front of the alkane name, as in cyclopropane and cyclobutane (Figure 11). If branches are present, treat the cycloalkane as the parent chain and identify the branches. Since there is no end at which to start the numbering for the location of the branches, use the lowest possible numbers.

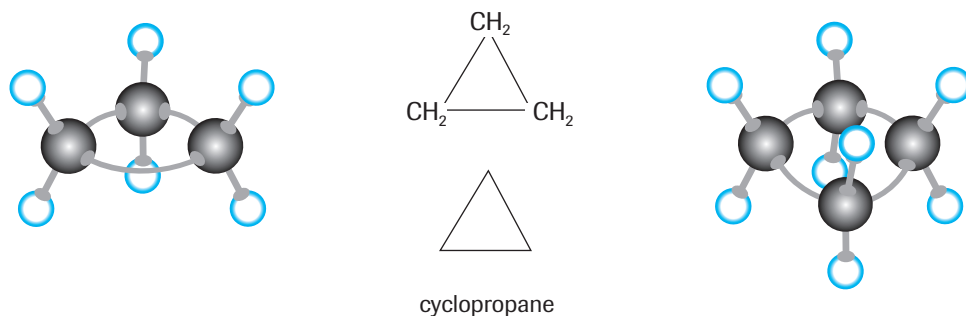


Figure 11

Cycloalkanes such as cyclopropane and cyclobutane are similar to alkanes, except that the two ends of the molecule are joined to form a ring of atoms. This figure shows computer-generated, condensed structural, and line structural models of these two cycloalkanes. These models help to provide a logically consistent theoretical explanation for empirically determined formulas and help chemists to visualize the molecules.

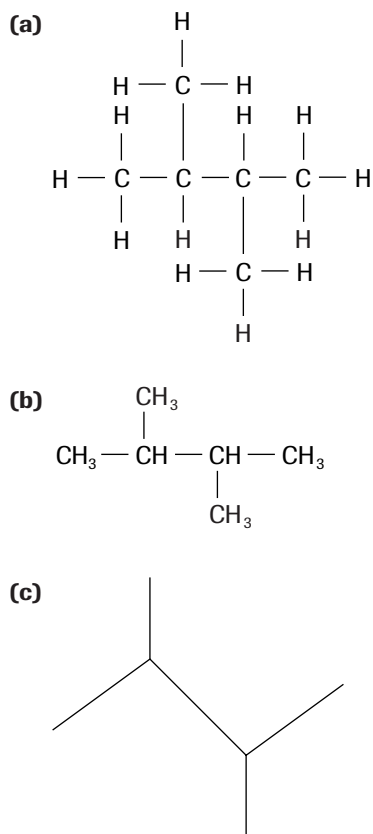


Figure 12

2,3-dimethylbutane can be represented by

- (a) a structural formula,
 (b) a condensed structural formula,
 or
 (c) a line structural formula.

Start with the location of one of the branches. Omit the “1” if only one branch is present. For example, methylcyclopropane is a cyclopropane ring with a methyl branch on one of three equivalent carbon atoms of the ring.

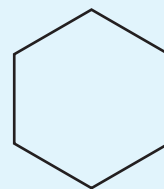
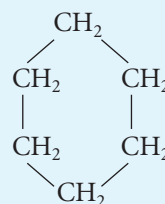
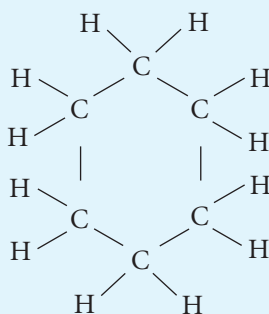
In addition to structural and condensed structural formulas, we can use *line structural formulas*. Line structural formulas of hydrocarbons show the position of the carbon atoms as the intersections and ends of bonding lines; they do not show hydrogen atoms (**Figure 12(c)**).

► COMMUNICATION example 3



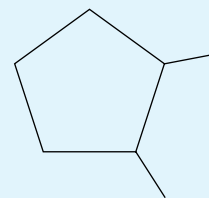
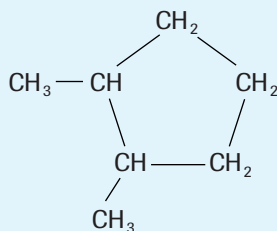
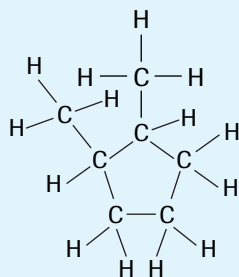
Provide structural, condensed structural, and line structural formulas for cyclohexane.

Solution



► COMMUNICATION example 4

Write the IUPAC name for this hydrocarbon, communicated with a structural, a condensed structural, and a line structural formula.



Solution

1,2-dimethylcyclopentane

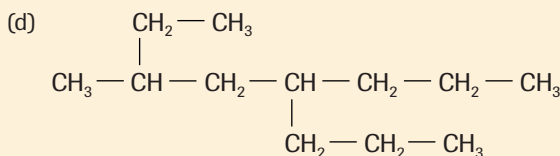
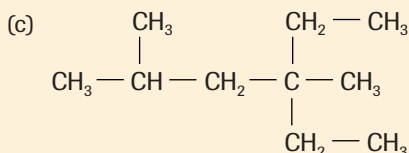
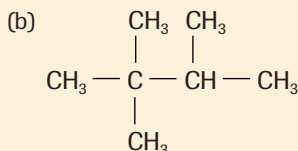
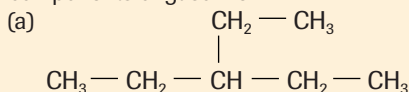
Note that rotating the 1,2-dimethylcyclopentane molecule in Communication Example 4 does not change its name—all of the formulas represent 1,2-dimethylcyclopentane. We count from the carbon atom that gives the lowest possible first number.

► Section 9.2 Questions

- List the alkanes that are typically present in natural gas before it is refined. How does this composition compare with the natural gas you use in your homes for heating?
- What is the difference between sweet and sour natural gas? Why is it important to know the difference?
- Describe a process used to remove alkanes, other than methane, from natural gas.
- Natural gas burns readily with oxygen from the air. The primary product is energy.
 - List two consumer, two commercial, and two industrial uses of the energy obtained from natural gas.
 - Look around the room you are in. List some items in the room that likely required energy from natural gas for their production.

5. Draw structural formulas for all reactants and products in the following organic reactions:
- methane + butane $\rightarrow$ pentane + hydrogen
 - propane + pentane $\rightarrow$ octane + hydrogen
 - decane + hydrogen $\rightarrow$ heptane + propane
 - 3-ethyl-5-methylheptane + hydrogen $\rightarrow$
ethane + propane + methylbutane
 - cyclohexane + ethane $\rightarrow$ ethylcyclohexane + hydrogen

6. Write the IUPAC names for each of the following possible components of gasoline:



7. For each of the following chemical equations, write the IUPAC names for all reactants and products.
- $\text{CH}_3 - \text{CH}_2 - \text{CH}_3 + \text{CH}_3 - (\text{CH}_2)_3 - \text{CH}_3 \rightarrow$
 $\text{CH}_3 - (\text{CH}_2)_6 - \text{CH}_3 + \text{H} - \text{H}$
 - $\text{CH}_3 - (\text{CH}_2)_4 - \text{CH}_3 \rightarrow$

$$\begin{array}{c} \text{CH}_3 \\ | \\ \text{CH}_3 - \text{C} - \text{CH}_2 - \text{CH}_3 \\ | \\ \text{CH}_3 \end{array}$$
 - Draw condensed structural and line structural formulas, and write the IUPAC names for two other isomers of the product given in (b).
8. Complete the following equations for complete combustion, using molecular formulas to write a balanced chemical equation. Include the structural formula or IUPAC name for each hydrocarbon.
- 2,2,4-trimethylpentane + oxygen $\rightarrow$
 - $$\begin{array}{c} \text{CH}_3 \\ | \\ \text{CH}_3 - \text{CH} - \text{CH}_2 - \text{CH}_3 \end{array} + \text{O} = \text{O} \rightarrow$$
 - $$\text{Cyclopentane} + \text{O} = \text{O} \rightarrow$$
9. Why do companies find and develop petroleum resources? Suggest an answer from at least two perspectives.

10. (a) Use the information in **Table 5** to plot a graph showing the relationship between the number of carbon atoms and the boiling points of the alkanes. Describe the relationship and propose an explanation for it.
- (b) Research a use for each of the first 10 alkanes, and suggest why each is appropriate for this use.

www.science.nelson.com



Table 5 Boiling Points of the First 10 Straight-Chain Alkanes

Formula	Name	B.p. (°C)
$\text{CH}_4(\text{g})$	methane	-161
$\text{C}_2\text{H}_6(\text{g})$	ethane	-89
$\text{C}_3\text{H}_8(\text{g})$	propane	-42
$\text{C}_4\text{H}_{10}(\text{g})$	butane	-1
$\text{C}_5\text{H}_{12}(\text{l})$	pentane	36
$\text{C}_6\text{H}_{14}(\text{l})$	hexane	68
$\text{C}_7\text{H}_{16}(\text{l})$	heptane	98
$\text{C}_8\text{H}_{18}(\text{l})$	octane	125
$\text{C}_9\text{H}_{20}(\text{l})$	nonane	151
$\text{C}_{10}\text{H}_{22}(\text{l})$	decane	174

11. Use the information in this section and from your own research to continue gathering perspective statements concerning the statement that the burning of fossil fuels should be reduced.

Extension

12. Oil spills in Alberta or near water, like the 2005 rail-car spill near Wabamum, cause a wide variety of environmental problems. Use your knowledge of alkanes to describe and explain what happens physically and chemically when oil is spilled from a tanker car into water.
13. Alberta has extensive natural gas fields that supply gas for use by provincial consumers and industries. The Alberta government collects royalties on the production of all fossil fuels, including natural gas.
- Describe or sketch a map of the distribution of natural gas fields in Alberta.
 - Approximately how much natural gas is produced in one year and how much of it is used within Alberta?
 - How much royalty has the Alberta government collected recently for natural gas? How does this sum compare with the total royalties the Alberta government collects for non-renewable resources?

www.science.nelson.com



14. Aboriginal peoples used waxes to waterproof footwear, bags, and other clothing. Technologically, paraffins are alkanes with twenty or more carbons; for example, $\text{C}_{25}\text{H}_{52}(\text{s})$. Explain why waxes, such as paraffin, can be used as a waterproofing agent.

www.science.nelson.com



9.3 Alkenes and Alkynes—Cracking Natural Gas

DID YOU KNOW?

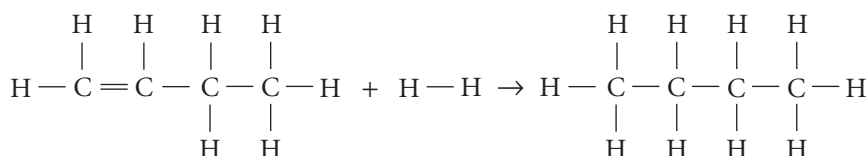
Margarine

Margarine containing vegetable oils whose molecules have many double bonds is said to be *polyunsaturated*. The molecules of *saturated* fats, in animal products such as butter, are fully hydrogenated (have only single bonds).

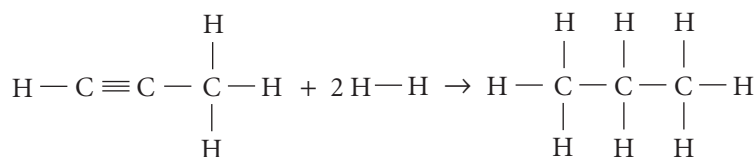
Alkenes and Alkynes

Analysis reveals that hydrocarbons containing double or triple covalent bonds make up a small percentage of petroleum (such as crude oil and natural gas). These compounds are also often formed during chemical refining and are valuable components of gasoline. Hydrocarbons containing double or triple bonds are important in the petrochemical industry because they are the starting materials for the manufacture of many derivatives, including plastics.

A double or a triple bond between two carbon atoms in a molecule affects the chemical and physical properties of the molecule. Organic compounds with carbon–carbon double or triple bonds are said to be **unsaturated**, because they have fewer hydrogen atoms than compounds with carbon–carbon single bonds. Unsaturated hydrocarbons can react readily (usually in the presence of a catalyst) with small diatomic molecules, such as hydrogen. This type of reaction is an addition reaction. Addition of a sufficient quantity of hydrogen, called **hydrogenation**, converts unsaturated hydrocarbons to saturated ones. Saturated hydrocarbons (alkanes) have no double or triple bonds. An excess of hydrogen is needed to convert an alkyne to an alkane, otherwise some of the alkyne is only converted to an alkene.



unsaturated hydrocarbon (e.g., an alkene) + hydrogen → saturated hydrocarbon



unsaturated hydrocarbon (e.g., an alkyne) + excess hydrogen → saturated hydrocarbon

Hydrocarbons with carbon–carbon double bonds are members of the **alkene** family (Figure 1). They all have the general formula of C_nH_{2n} . The names of alkenes with only one double bond have the same prefixes as the names of alkanes, together with the ending *-ene* (Table 1). (Ethene is the starting material for a huge variety of consumer, commercial, and industrial products, some of which are listed in Chapter 10, page 415.) Isomers exist for all alkenes larger than propene. Cycloalkanes are isomers of alkenes.

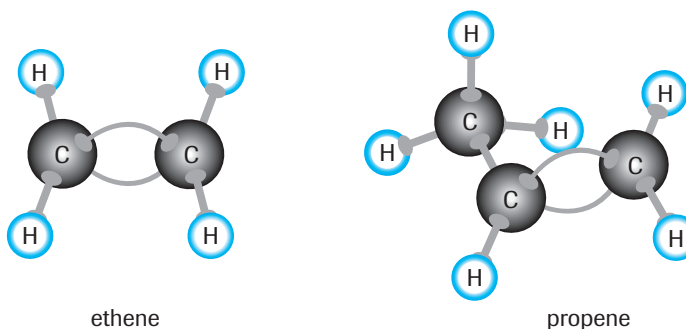
Table 1 The Alkene Family of Organic Compounds

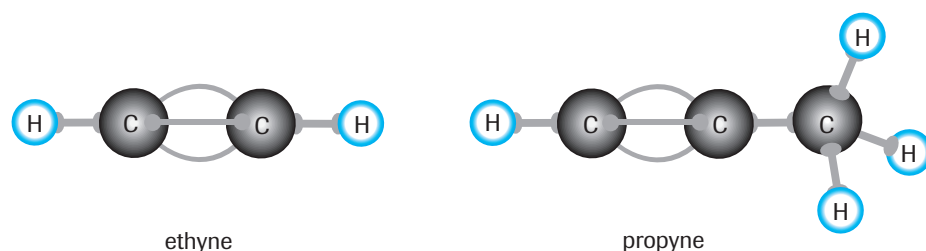
IUPAC name (common name)	Molecular formula
ethene (ethylene)	$\text{C}_2\text{H}_4(\text{g})$
propene (propylene)	$\text{C}_3\text{H}_6(\text{g})$
but-1-ene (butylene)	$\text{C}_4\text{H}_8(\text{g})$
pent-1-ene	$\text{C}_5\text{H}_{10}(\text{l})$
hex-1-ene	$\text{C}_6\text{H}_{12}(\text{l})$
-ene	C_nH_{2n}

Note: See Naming Alkenes and Alkynes on the next page for an explanation of the numbering system.

Figure 1

The two simplest and most commonly used alkenes are ethene (known as ethylene) and propene (propylene).



**Figure 2**

Sophisticated laboratory research indicates that the triple covalent bonds of ethyne (acetylene) and propyne are the shortest, strongest, and most reactive of all carbon–carbon bonds.

The **alkyne** family has chemical properties that can be explained only by the presence of a triple bond between carbon atoms (**Figure 2**). Like alkenes, alkynes are unsaturated and can react with small molecules such as hydrogen or bromine in an addition reaction. Alkynes are named like alkenes, except for the *-yne* ending. The simplest alkyne, ethyne (acetylene), is commonly used in an oxyacetylene torch for cutting and welding metals. **Table 2** lists the first five members of the alkyne family. Empirical studies indicate that all alkynes with one triple bond have the general formula C_nH_{2n-2} . Isomers exist for all alkynes larger than propyne. Cycloalkenes are isomers of alkynes.

Naming Alkenes and Alkynes

Since the location of a multiple bond affects the chemical and physical properties of a compound, an effective naming system should specify the location of the multiple bond. Alkenes and alkynes are named much like alkanes, with two additional points to consider.

- The longest or parent chain of carbon atoms must contain the multiple bond, and the chain is numbered from the end closest to the multiple bond.
- The number that indicates the position of the multiple bond on the parent chain precedes the ending (*-ene* or *-yne*) of the parent chain.

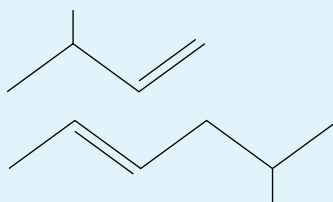
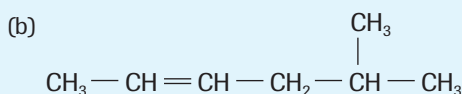
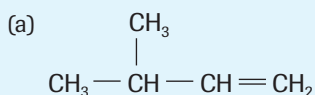
For example, there are two possible butene isomers, but-1-ene and but-2-ene.



Note that the number in front of the ending specifies the location of the multiple bond, just as the number in front of the branch indicates its location.

COMMUNICATION example 1

Name the hydrocarbons communicated by the following condensed structural and line structural formulas.



Solution

The IUPAC name for (a) is 3-methylbut-1-ene.

The IUPAC name for (b) is 5-methylhex-2-ene.

Table 2 The Alkyne Family of Organic Compounds

IUPAC name (common name)	Molecular Formula
ethyne (acetylene)	$C_2H_2(g)$
propyne	$C_3H_4(g)$
but-1-yne	$C_4H_6(g)$
pent-1-yne	$C_5H_8(l)$
hex-1-yne	$C_6H_{10}(l)$
-yne	C_nH_{2n-2}

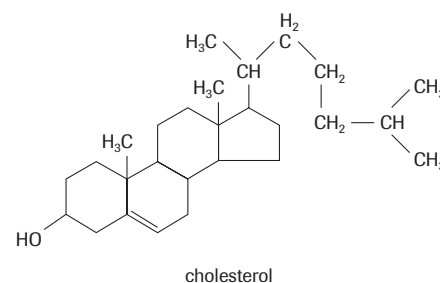
DID YOU KNOW?

Steroids

Steroids are unsaturated compounds based on a structure of four rings of carbon atoms. The best known and most abundant steroid is cholesterol, which is an essential constituent of cell walls, but which has also been associated with diseases of the cardiovascular system. Cholesterol that coats the interior surfaces of arteries contributes to health problems such as high blood pressure. Other steroids include the male and female sex hormones, and anti-inflammatory agents such as cortisone. Oral contraceptives include two synthetic steroids. Some athletes have used anabolic steroids to enhance muscle development and physical performance, but such use may cause permanent damage.

You can view a computer-generated 3-D molecular model of cholesterol by visiting the Nelson Web site.

www.science.nelson.com



Learning Tip

Note that the numbering of carbons for alkenes and alkynes always starts from the end of the molecule closest to the double or triple bond(s). This method yields the lowest possible number for the position of the multiple bond.

Learning Tip

The two general rules used throughout organic nomenclature are:

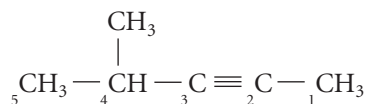
- use the longest continuous chain containing the primary characteristic group of the molecule to determine the prefix and ending of the parent name

Prefix (number of C atoms in longest chain)	+Ending (characteristic group)
e.g., meth (1)	ane (C—C)
eth (2)	ene (C=C)
prop (3)	yne (C≡C)

For example,
2-methylhexane
2-methylhex-3-ene
2-methylhex-3-yne

- use the lowest set of numbers to indicate the first characteristic feature and then the branches or substituents in the molecule

In the following branched alkyne structure, the parent chain is a pentyne.



4-methylpent-2-yne

When numbering the carbon atoms of an alkene or alkyne parent chain, chemists give more importance to the location of the multiple bond(s) than to the location of any branches (alkyl groups). The IUPAC name, 4-methylpent-2-yne, follows the same format as that used for alkanes.

Drawing Structural Formulas of Alkenes and Alkynes

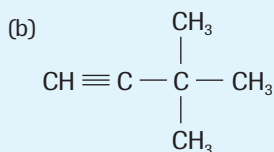
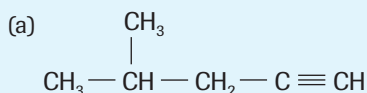
Whenever you need to draw a structural formula for any hydrocarbon, first look at the end of the name to find the parent chain. Draw the parent alkene or alkyne first, and then add the branches listed in the name. Be sure to finish the formula with sufficient hydrogen atoms to complete four bonds for each carbon atom. The following Communication Example shows some typical examples of alkenes and alkynes.

COMMUNICATION example 2

Draw condensed structural formulas for the following alkyne petrochemicals:

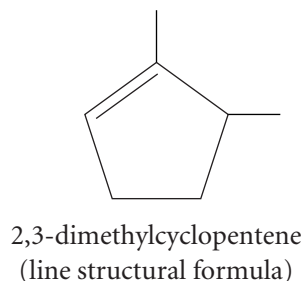
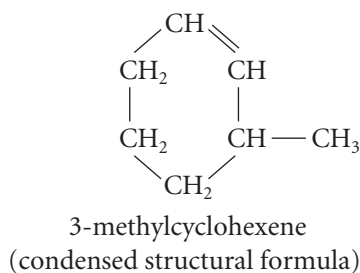
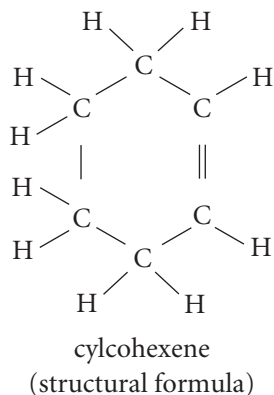
- (a) 4-methylpent-1-yne
- (b) dimethylbut-1-yne

Solution



Cycloalkenes and Cycloalkynes

In addition to alkanes, cycloalkanes, alkenes, and alkynes, chemists discovered hydrocarbons whose properties can only be explained by creating a new class of hydrocarbons, called **cycloalkenes**. As the name of this class of hydrocarbons suggests, its molecules have a cycle of carbon atoms with at least one double bond. The structural formulas and names of cycloalkenes follow the same IUPAC rules as those for cycloalkanes. Here are some examples.



Note that, when naming cycloalkenes with side branches, the numbering for the carbon atoms begins with the double bond: the carbons of the double bond are carbons 1 and 2. The carbons are numbered so as to provide *the lowest numbers possible*, as for all other hydrocarbons. The system for naming all hydrocarbons is logically consistent—the same rules apply to all classes of hydrocarbons.

There are few known cycloalkenes and cycloalkynes. Chemists explain this low membership by considering the bond-angle stress put on the double and triple bonds when a cyclic hydrocarbon is created.

Cycloalkanes are isomers of alkenes with the same number of carbon atoms, both with the general formula C_nH_{2n} . Similarly, cycloalkenes are isomers of alkynes, both with the general formula C_nH_{2n-2} . Isomers of alkenes and alkynes exist with different locations of the double or triple bond and by changing a straight-chain hydrocarbon into a branched hydrocarbon or into a cyclic hydrocarbon. If you find that several structures have the same formula but different names, then the structures are isomers. For example, cyclohexene is an isomer of a simple hexyne. Both have the same molecular formula, $C_6H_{10}(l)$ (Figure 3).

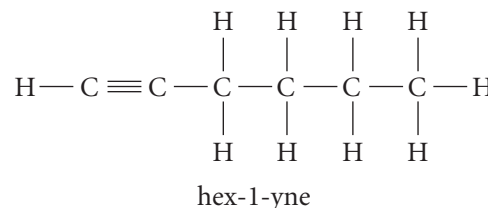
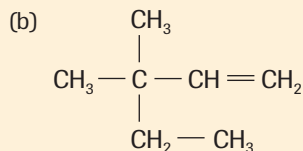
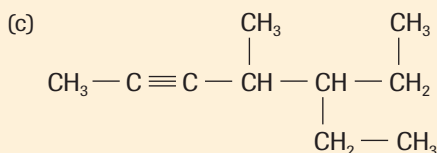
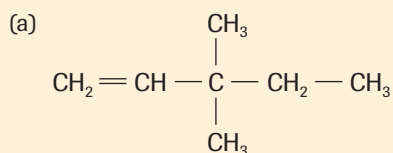


Figure 3

Hex-1-yne is an isomer of cyclohexene. Cycloalkenes are isomers of alkynes and vice versa.

Practice

- Classify each of the following hydrocarbons as an alkane, alkene, or alkyne, and/or as a cycloalkane or cycloalkene:
 - $C_2H_4(g)$
 - $C_3H_8(g)$
 - $C_4H_6(g)$
 - $C_5H_{10}(l)$
- Draw a structural formula and write a molecular formula for each of the following:
 - propane
 - propene
 - propyne
 - cyclopropane
- Draw a condensed structural formula for each of the following petrochemicals.
 - propene
 - but-2-ene
 - 2,4-dimethylpent-2-ene
 - but-1-yne
- Why are no numbers required for the location of the multiple bond in propene or propyne?
- Draw line structural formulas and write IUPAC names for each of the following structures:



- Draw line structural formulas and write the IUPAC names for the four structural isomers of $C_4H_8(g)$. (Remember cyclo compounds.)
- Alkenes and alkynes are the starting materials in the manufacture of a wide variety of organic compounds. Draw structural formulas for the following starting materials that are used to make the products named in parentheses.
 - propene (polypropylene)
 - methylpropene (synthetic rubber)

+ EXTENSION



Interactive Models

There are more and more computer-generated 3-D molecular models being created on Web sites. These models help chemists, teachers, and students to visualize the structures of molecules. (Crystallographic research from, for example, X-ray analysis, provides the data points for the atoms.) Most of the computer models allow you to select line, ball-and-stick, and space-filling models. You can also rotate the molecule by using your computer mouse. Many examples are provided at the following link. Using Internet resources such as this will help to increase your knowledge and feel for organic molecules.

www.science.nelson.com





INVESTIGATION 9.2 Introduction

Report Checklist

- | | | |
|----------------------------------|---|---|
| ☐ Purpose | ☐ Design | ☒ Analysis |
| ☐ Problem | ☐ Materials | ☒ Evaluation (3) |
| ☐ Hypothesis | ☐ Procedure | |
| ☐ Prediction | ☒ Evidence | |

Structures and Properties of Isomers

Molecular models are visual representations of molecules that help us to understand some of the properties and structures of molecules. In addition to building models, this investigation asks you to consult references to obtain data gathered by chemists over many years of laboratory work.

Purpose

The purpose of this investigation is to use models and a reference, respectively, to examine the structures and physical properties of some isomers of unsaturated hydrocarbons.

Problem

What are the structures and physical properties of the isomers of C_4H_8 and C_4H_6 ?

Design

Structures of possible isomers are determined by means of a molecular model kit. Once each structure is named, the boiling and melting points are obtained from a reference such as the *CRC Handbook of Chemistry and Physics* or *The Merck Index*.

To perform this investigation, turn to page 401.

Table 3 Boiling Points of Simple Alkanes in Natural Gas

Alkane	Boiling point (°C)
methane	-162
ethane	-89
propane	-42
methylpropane	-12
butane	-0.5
dimethylpropane	10
methylbutane	28
pentane	36

Ethane Cracking

The low boiling points in natural gas make it difficult to separate these components (Table 3). Alberta has several specialized gas plants where the various components of natural gas are separated. (See the list in the margin: Ethane Extraction Plants.) The condensation of the natural gas components is achieved with temperatures down to $-100\text{ }^{\circ}\text{C}$ and pressures up to 1500 to 5000 kPa (15 to 50 atm). The components are also known as LPGs (liquid petroleum gases) and are sold separately (or as a mixture) once they are removed from natural gas. The most familiar LPG to us is propane, used for combustion in barbecues, automobiles, and homes. From a chemical industry perspective, the most important LPG is ethane, used for manufacturing ethene. The uncondensed methane is returned to the natural gas pipeline for consumer, commercial, or industrial combustion or petrochemical use. Methane is the refined natural gas that may heat your home and your water.

Ethene (ethylene) is produced world wide by cracking either ethane or naphtha (a mixture of C_5 – C_7 hydrocarbons). **Cracking** is an industrial process in which larger hydrocarbon molecules are broken down at high temperatures, with or without catalysts, to produce smaller hydrocarbon molecules. The large hydrocarbon molecules are known as cracking stock. Since there is a large quantity of ethane available from natural gas in Alberta, ethene is manufactured in western Canada by cracking ethane. First the ethane must be extracted from the natural gas. According to Table 1 on page 363, a typical mole fraction of ethane in natural gas is 11.6% (although this value can vary considerably).

The ethane that is separated from the natural gas is put in a pipeline and piped to an ethane cracking plant in Alberta (such as the one in Joffre) or in eastern Canada or the United States. Sometimes the LPGs are stored in large salt caverns 1 to 2 km below the surface (Figure 4).

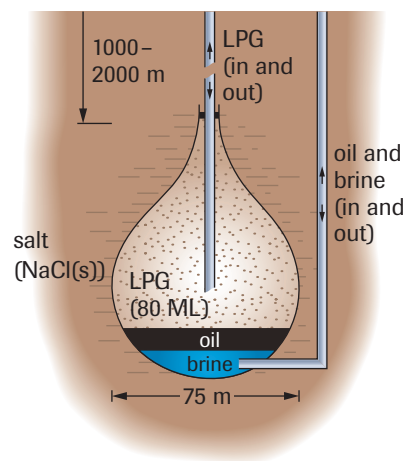


Figure 4

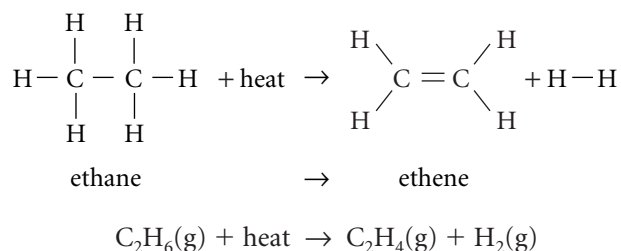
The salt caverns near Fort Saskatchewan, Alberta are enormous: about 80 ML or 80 km^3 . Situated at least 1 km below the surface, a typical salt cavern holds a volume equivalent to about 32 Olympic-size swimming pools.

Learning Tip

The use of the term “cracking” in this chapter has two meanings. The first meaning, presented here, is that of removing (cracking) hydrogen from ethane to produce ethene. Technically this is not “real” cracking, but *ethane cracking* is a widely used term in industry.

The meaning presented in Section 9.5 is that of breaking or cracking a molecule between two carbon atoms to make smaller hydrocarbon molecules. This is the more common usage of the term cracking.

Ethane cracking is also called dehydrogenation. The term cracking usually refers to breaking a large molecule down into a smaller molecule. In the case of ethane cracking, two hydrogen atoms are removed (“cracked”) from an ethane molecule to convert it into an ethene molecule. A catalyst is used to increase the rate of the reaction and the hydrogen product is used in the plant.



You will find out much more about the reactions of ethane and ethene in Chapter 10. As with most chemical processes, the process is not as simple as the equation suggests. Temperature and pressure must be optimized, and a suitable catalyst must be found through experimentation. The incoming gas must be very pure: impurities such as carbon dioxide must be removed before cracking. During cracking, many side reactions produce hydrocarbons such as methane, ethyne (acetylene), propane, and butane. For economic and environmental reasons, some of the by-products are burnt rather than released into the atmosphere. The propene made at Joffre is sold as feedstock to produce other products, and the hydrogen is used to make ammonia (used in fertilizer production).

Aliphatic Hydrocarbons

So far you have encountered many different kinds of hydrocarbons: some with straight chains, some with branches, and some that are cyclic. You have also learned about saturated and unsaturated hydrocarbons. All of these compounds are classed together as **aliphatic hydrocarbons**. In the next section, you will encounter another class of hydrocarbons: the aromatics.

SUMMARY *Alkenes and Alkynes*

- Alkenes are hydrocarbons that contain at least one carbon–carbon double bond, usually C_nH_{2n} ; e.g., propene, $\text{C}_3\text{H}_6(\text{g})$ or $\text{CH}_2=\text{CH}-\text{CH}_3$.
- Alkynes are hydrocarbons that contain at least one carbon–carbon triple bond, usually $\text{C}_n\text{H}_{2n-2}$; e.g., propyne, $\text{C}_3\text{H}_4(\text{g})$ or $\text{CH}\equiv\text{C}-\text{CH}_3$.
- Alkenes and alkynes are unsaturated compounds that are easily converted to saturated (alkane) compounds by the addition of hydrogen (called hydrogenation).

$$\text{alkene/alkyne} + \text{H}_2(\text{g}) \rightarrow \text{alkane}$$
 e.g., but-2-ene + hydrogen $\rightarrow$ butane

$$\text{CH}_3-\text{CH}=\text{CH}-\text{CH}_3 + \text{H}-\text{H} \rightarrow \text{CH}_3-\text{CH}_2-\text{CH}_2-\text{CH}_3$$
- Rules for Naming
 - Number the longest chain containing the multiple bond from the end closer to the multiple bond.
 - Identify the type and location of each branch.
 - Write the IUPAC name using the format:
 (branch location)-(branch name)(prefix)-(multiple bond location)-(ene/yne);
 e.g., 4-methylpent-2-ene
- Alkenes are isomers of cycloalkanes and alkynes are isomers of cycloalkenes.
- The cracking of ethane to ethene is a very important chemical reaction in Alberta.

DID YOU KNOW?

Ethane Extraction Plants

Alberta has over a dozen plants that extract (fractionate) ethane from natural gas. The ethane is gathered and distributed by pipelines.

The major extraction plants include

- Cochrane
- Empress
- Joffre

Other locations include

- Harmattan
- Judy Creek (near Swan Hills and Barrhead)
- Jumping Pound (near Sibbald Flats)
- Bonnie Glen (near Wetaskiwin)
- Waterton (near Pincher Creek)
- Elmworth and Wapiti (near Grande Prairie)
- Edmonton (23 Avenue)

Is there an ethane extraction plant near you?

Learning Tip

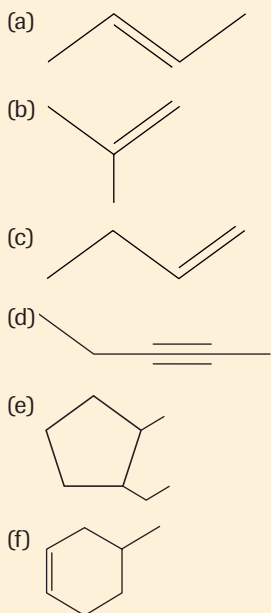
Classroom research indicates that the kind of learning required here is assisted by memorizing the rules, practising on many examples, and learning from your initial mistakes.

Initially there is a lot of memorizing, but eventually the logic of the nomenclature systems and of the structural formulas becomes easy when you persevere.

Section 9.3 Questions

- Alkanes, alkenes, and alkynes are the three main families of aliphatic hydrocarbons.
 - What is the general molecular formula for each family?
 - What is the main structural feature of each family?
 - Why does the number of hydrogen atoms in the molecular formula decrease by two as you go from alkanes to alkenes, and then to alkynes?
- Why are there more possible isomers of an alkene than an alkane with the same number of carbon atoms?
- State one major use of the first member of the alkene and alkyne families.
- Explain what is meant by the term “unsaturated” as applied to a hydrocarbon.
- Draw structural formulas and write IUPAC names for the five aliphatic structural isomers of C_5H_{10} .
- Write IUPAC names for the following hydrocarbons that are communicated as condensed structural formulas.
 - $CH_3 - CH_2 - CH_2 - CH_2 - CH_3$
 - $CH_3 - CH = CH - CH_2 - CH_3$
 - $CH \equiv C - CH_2 - CH_2 - CH_3$
 - $CH_2 = CH - CH_2 - CH_3$
 - $$\begin{array}{c}
 CH_3 - CH - CH = CH - CH_3 \\
 | \\
 CH_3
 \end{array}$$

- Write IUPAC names for the following hydrocarbons that are communicated as line structural formulas.



- Use structural or condensed structural formulas for some simple cycloalkanes to determine the general molecular formula for cycloalkanes.

- Draw a line structural formula and write the IUPAC name for a cyclic hydrocarbon that is a structural isomer of but-1-yne.
- Draw condensed structural formulas, labelled with IUPAC names, for all the straight-chain isomers of $C_4H_6(g)$.
- Draw a line structural formula for each of the following hydrocarbons:
 - 3-ethyl-4-methylpent-2-ene
 - 5-ethyl-2,2,6-trimethylhept-3-yne
- Use the information in this section and from your own research to continue gathering pro and con perspective statements concerning the resolution that the burning of fossil fuels should be reduced.

Extension

- Ethyne (acetylene) is used in large quantities by industrial processes. Normally, gaseous substances are liquefied under high pressure and stored in steel cylinders in order to provide a reasonably large quantity for use; cylinders of propane are a typical example. Research why it is not advisable to highly compress acetylene, and how solubility is used to store $C_2H_2(g)$ in cylinders. Present your findings.

www.science.nelson.com



- Use a map of Alberta to find where the ethane extraction and ethane cracking plants are located. Which one is closest to where you live? In what ways does the presence of this plant affect you or your community?

www.science.nelson.com



- Use the Internet to find the home page of one of the companies involved with ethane production in Alberta. Access their career or human resources page and find information on the education required to work there.

www.science.nelson.com



- Computer-generated 3-D molecular models communicate the research done by chemists and help everyone visualize the shape of molecules. Find some alkenes, alkynes, and cycloalkenes at the following Web link. How has your personal view of these molecules changed when moving from viewing 2-D static models in this textbook or elsewhere to viewing 3-D (interactive) models on the Internet?

www.science.nelson.com



Aromatics 9.4

Historically, organic compounds with an aroma or odour were called *aromatic compounds*. Today, chemists define **aromatics** as benzene, $C_6H_6(l)$, and all other carbon compounds that contain benzene-like structures and properties. Aromatic hydrocarbons are found naturally in petroleum (such as crude oil and natural gas) and are most often burned. Research has identified benzene as a potential carcinogen (cancer-producing substance), however. As a result, government legislation and industry innovations have reduced the benzene content of, for example, gasoline to no more than 1%. At the same time, refinery emissions of benzene have been reduced by about 90%. Research on urban air quality has shown that these reductions have, in fact, improved the air breathed by urbanites.

The molecular structure of benzene intrigued chemists for many years because they could not explain the properties of this compound (listed below), using accepted theories of bonding and reactivity.

- The molecular formula of benzene, based on its percentage composition and molar mass, is C_6H_6 .
- The melting point of benzene is $5.5\text{ }^{\circ}\text{C}$, the boiling point is $80.1\text{ }^{\circ}\text{C}$, and tests show that the molecules are non-polar.
- There is no empirical support for the idea that there are double or triple bonds in benzene. For example, it is very unreactive with hydrogen.
- X-ray diffraction indicates that all the carbon–carbon bonds in benzene are the same length.
- Evidence from chemical reactions indicates that all carbons in benzene are identical and that each carbon is bonded to one hydrogen.

The empirical formula for benzene, $C_6H_6(l)$, was determined in 1825 by Michael Faraday (1791–1867). Visualizing a model of the benzene molecule that followed accepted bonding rules proved difficult. Finally, in 1865, August Kekulé (1829–1896) proposed a cyclic structure for benzene. The combination of the theoretical work on structural formulas by Kekulé and the empirical work of Josef Loschmidt (1821–1895) proved fruitful. Since evidence indicates that all bonds between the carbon atoms in benzene are identical in length and in strength, an acceptable model requires the even distribution of the extra six unbonded valence electrons around the entire molecule (**Figures 1 and 2**). Consider this molecule as having six unbonded valence electrons distributed around a 6-carbon-atom ring, forming a strong hexagonal structure.

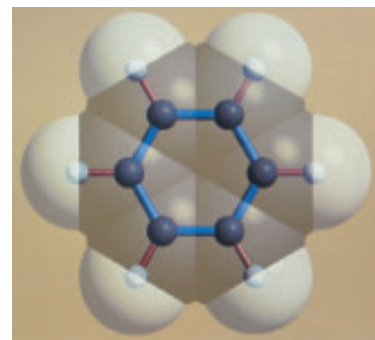


Figure 1 Although Loschmidt and others had proposed several hypotheses for the structure of benzene (C_6H_6), Kekulé championed a hexagon model. The evidence from structural isomers and chemical reactions and the logical consistency of this model with the bonding capacities of carbon and hydrogen led to the acceptance of the hexagon hypothesis (model) by the chemistry community.

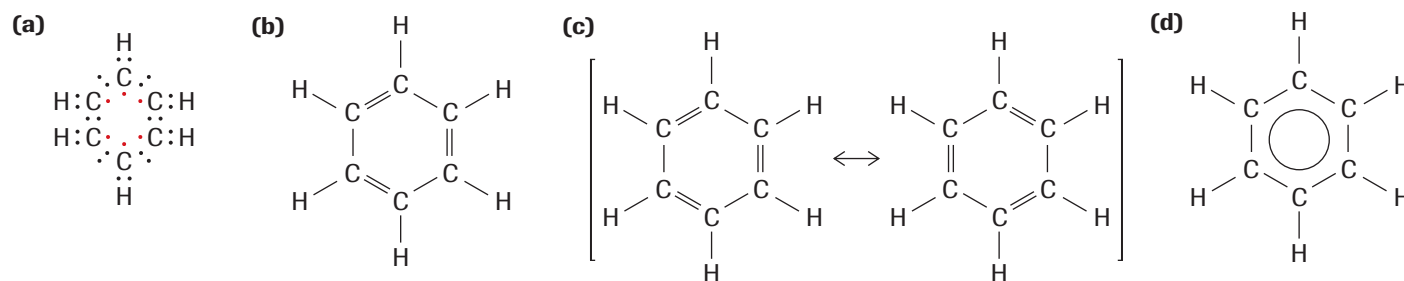
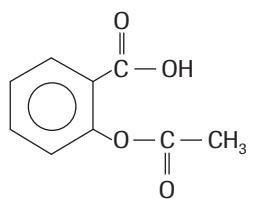
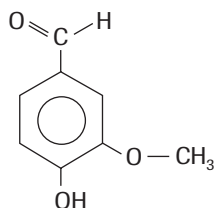


Figure 2

A progressive series of models of benzene: **(a)** agrees with the evidence but is not consistent with the theory that carbon forms four bonds with other atoms; **(b)** disagrees with the evidence but is consistent with the four-bond theory for carbon; **(c)** is closer to the evidence and is consistent with the four-bond theory; **(d)** represents a new theory that agrees with the evidence; and **(e)** is a line structural formula that represents the new theory—the sharing of six valence electrons among six carbon atoms.



Aspirin®
(ASA, acetylsalicylic acid)



vanillin

Figure 4

Common aromatic compounds include Aspirin® and vanillin. Vanillin is one of the flavour molecules in vanilla. You will notice that many aromatic molecules are often depicted using a condensed structural formula except for the benzene ring, which is shown as a line structural formula. This combination is commonly used by chemists.

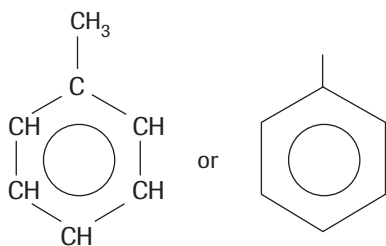
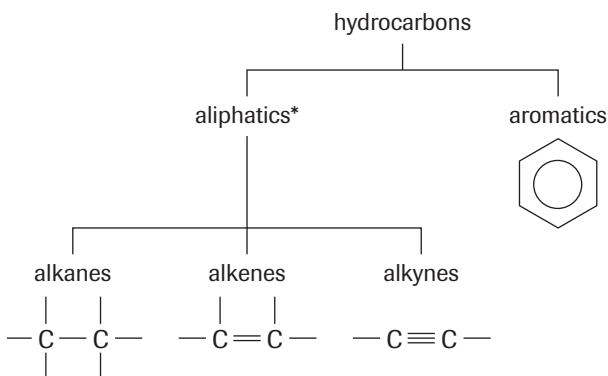


Figure 5

Methylbenzene ($C_6H_5CH_3(l)$), commonly known as toluene, is a solvent used in glues and lacquers. It is toxic to humans but is preferred to benzene as a solvent because benzene is both toxic and carcinogenic.

Figure 6

Three isomers of diethylbenzene. The *o*-, *m*-, and *p*- classical nomenclature is described in the Learning Tip on the next page.



*includes cyclo compounds of each family

Figure 3

Aliphatic and aromatic hydrocarbons

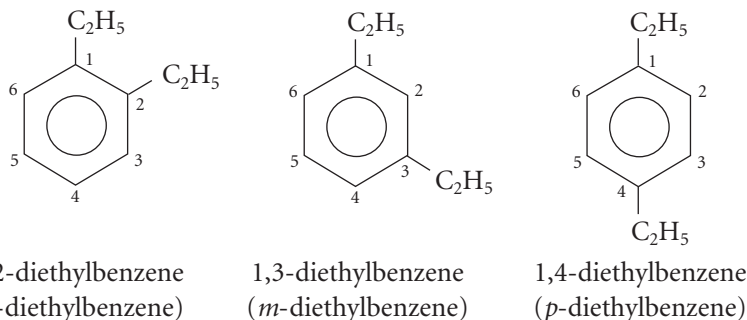
Based on the evidence of the properties of benzene, this structure must be particularly stable. The reactions of benzene are similar to those of alkanes—benzene behaves chemically like a saturated hydrocarbon (an alkane). Since 1865, hydrocarbons were classified as aliphatic or aromatic (**Figure 3**). For our purposes, aromatic compounds contain the benzene ring, which is represented by a hexagon with an inscribed circle. Structures of all aromatic compounds include bonding similar to that in the benzene ring (**Figure 4**).

Naming Aromatics

Simple aromatics are usually named as relatives of benzene. If an alkyl group is bonded to a benzene ring, it is named as an alkylbenzene (**Figure 5**). The alkyl group is considered a substitute for a hydrogen atom. Since all of the carbon atoms of benzene are equivalent to each other, no number is required in the names of compounds of benzene that contain only one branch.

When two hydrogen atoms of the benzene ring have been substituted, three isomers are possible. These isomers are named as alkylbenzenes, using the lowest possible pair of numbers to indicate the locations of the two alkyl groups on the benzene ring. The numbering starts at one of the branches and goes clockwise or counterclockwise to obtain the lowest possible pair of numbers (**Figure 6**).

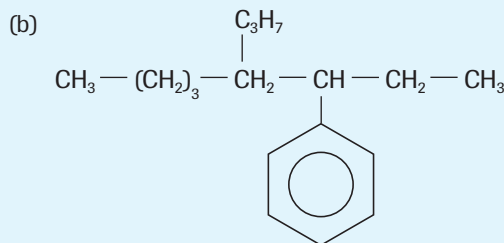
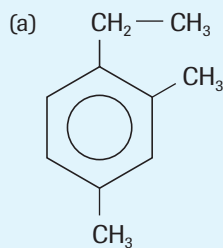
For some larger molecules, it is more convenient to consider the benzene ring as a branch. In such molecules, the benzene ring is called a **phenyl group**, $-C_6H_5$. For example, the compound in **Figure 7** is named 2-phenylpentane, according to the naming system for branched alkanes (page 368). Either naming system for aromatic compounds is acceptable; choose the more convenient method for the compound in question.



When drawing a structural formula from a name, carbon 1 can be designated anywhere on the benzene ring. The numbering 1 to 6 can be done clockwise or counterclockwise. The molecules do not know which way is up.

COMMUNICATION example

Write IUPAC names for the following aromatic hydrocarbons:



Solution

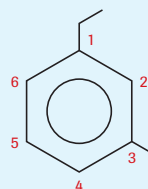
- (a) 1-ethyl-2,4-dimethylbenzene (b) 3-phenyl-4-propyloctane

When drawing a structural formula for an aromatic compound, always look at the end of the given name to identify the parent chain. Is the parent chain benzene or an aliphatic compound? Draw the parent chain first, then consider the placement of the branches.

SAMPLE problem 9.3

Draw the line structural formula for 1-ethyl-3-methylbenzene.

First, draw the benzene ring, and then add an ethyl group to any C atom of the ring; this C atom automatically becomes C 1 in the numbering system. Finally, add a methyl group to C 3, which can be clockwise or counterclockwise from C 1.



Note that, for line structural formulas, no hydrogen atoms are shown and the end of any line segment denotes a carbon atom.

SUMMARY Naming Aromatic Hydrocarbons

1. If an alkyl branch is attached to a benzene ring, the compound is named as an alkylbenzene. Alternatively, the benzene ring may be considered as a branch of a large molecule; in this case, the benzene ring is called a phenyl branch.
2. If more than one alkyl branch is attached to a benzene ring, the branches are numbered using the lowest numbers possible, starting with one of the branches. Given a choice between two sets of lowest numbers, choose the set that is in both numerical and alphabetical order. See Sample Problem 9.3.

WEB Activity

Web Quest—West Nile Denial

In this Web Quest, investigate traditional and modern mosquito repellents, and create a brochure to help people in the prairie provinces reduce the risk of contracting West Nile Virus.

www.science.nelson.com

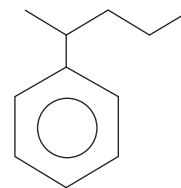


Figure 7

A line structural formula for 2-phenylpentane

Learning Tip

You may encounter a naming system—known as the classical system—for benzene rings with two substituted groups. The 1,2-, 1,3-, and 1,4-arrangements are denoted by the prefixes *ortho-* (*o*), *meta-* (*m*), and *para-* (*p*), respectively. These names, such as *o*-dimethylbenzene, are still used in industry, and you may encounter them in other references.

DID YOU KNOW?

VOCs

Volatile organic compounds (VOCs) are gases and vapours, such as benzene, that are released throughout the petroleum refining processes. Petrochemical plants (see Chapter 10), plastics manufacturing, and the distribution and burning of gasoline all release VOCs into the atmosphere. Some VOCs, like benzene, are carcinogens. Other VOCs react in sunlight with nitrogen oxides from automobile exhaust to form ground-level ozone, a component of smog.



LAB EXERCISE 9.A

Chemical Properties of Aliphatics and Aromatics

Comparing chemical properties of different classes of hydrocarbons can be difficult in a high school chemistry laboratory. Many hydrocarbons are volatile organic compounds (VOCs), some are carcinogenic (such as benzene), and many are flammable. In this investigation, the properties of aliphatics are compared to those of aromatics by reporting the evidence for the reaction of a cycloalkane, a cycloalkene, and an aromatic with potassium permanganate, a strong oxidizing agent. When completing the Prediction, provide a theoretical justification.

Purpose

The purpose of this investigation is to test the generalization that aromatic hydrocarbons react like saturated rather than unsaturated hydrocarbons.

Problem

What is the order of reaction rate for cyclohexane, cyclohexene, and benzene?

Report Checklist

- | | | |
|---|---------------------------------|--|
| ☐ Purpose | ☐ Design | ☒ Analysis |
| ☐ Problem | ☐ Materials | ☒ Evaluation (2, 3) |
| ☐ Hypothesis | ☐ Procedure | |
| ☒ Prediction | ☐ Evidence | |

Design

Each of cyclohexane, cyclohexene, and benzene is mixed vigorously with aqueous potassium permanganate in a fumehood. Evidence for a reaction is a change in the purple colour of the aqueous potassium permanganate.

Evidence

Cyclohexane

- Initially, no changes were observed in the mixture.
- After 5 min, the colour changed from purple to grey-purple.

Cyclohexene

- The colour of the mixture immediately changed to green.
- After 5 min, a brown precipitate formed.

Benzene

- Initially, no changes were observed in the liquid.
- After 5 min, the colour was still the same.



LAB EXERCISE 9.B

Boiling Points of Sample Aliphatics and Aromatics

Most of the hydrocarbons with smaller molecules, such as methane, ethane, propane, and butane, are gases at SATP. Hydrocarbons with medium-sized molecules (C_5 – C_{18}) are found to be liquids. We often fail to appreciate how easy it is to transport and dispense these liquid hydrocarbons. We can explain the relative boiling points of hydrocarbons theoretically with the concept of London forces. Evaluate the ability of the concept of London forces to predict the relative boiling points of different classes of hydrocarbons. (According to philosophers of science, in this lab exercise, you are testing the *predictive* power of a scientific concept.)

Purpose

The purpose of this lab exercise is to test the ability of the concept of London forces to predict the relative boiling points of aliphatic and aromatic hydrocarbons.

Report Checklist

- | | | |
|---|---------------------------------|--|
| ☐ Purpose | ☐ Design | ☒ Analysis |
| ☐ Problem | ☐ Materials | ☒ Evaluation (2, 3) |
| ☐ Hypothesis | ☐ Procedure | |
| ☒ Prediction | ☐ Evidence | |

Problem

What is the relative order of boiling points of simple C_6 alkane, alkene, cycloalkane, cycloalkene, and aromatic hydrocarbons?

Design

The boiling points of hexane, hex-1-ene, cyclohexane, cyclohexene, and benzene are obtained from *Lange's Handbook of Chemistry, 13th Edition*.

Evidence

Table 1 Boiling Points of C_6 Aliphatics and Aromatics

Hydro-carbon	Hexane	Hex-1-ene	Cyclo-hexane	Cyclo-hexene	Benzene
Boiling point ($^{\circ}C$)	68.7	63.5	80.5	83.0	80.10

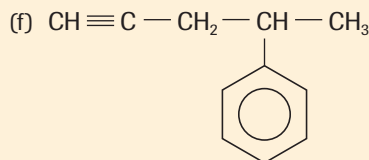
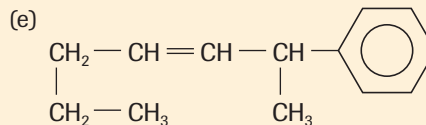
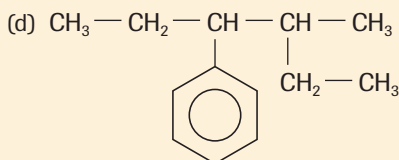
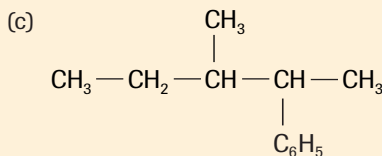
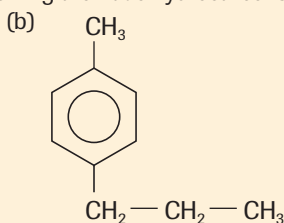
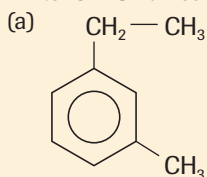
Section 9.4 Questions

- State the name and chemical formula of the simplest aromatic compound. In your own words, describe what is unusual about its structure.
- There are over 4000 dehydrators at natural gas well sites throughout Canada. The older technology allowed for emissions of benzene, methylbenzene (toluene), ethylbenzene, and the three dimethylbenzenes (xylenes). Newer technologies have been invented to reduce these emissions. Draw line structural formulas for each of these six aromatic compounds.
- Draw a combination of line and condensed structural formulas for the following aromatics:
 - 1,2,4-trimethylbenzene
 - 1-ethyl-2-methylbenzene
 - 3-phenylpentane
 - 3-methyl-1-phenylbutane
- The isomers of dimethylbenzene, commonly called xylenes, are used as solvents for adhesives (**Figure 8**). Write alternative IUPAC names and draw structural formulas for the three xylene isomers.
 - 1,4-dimethylbenzene
 - 1,3-dimethylbenzene
 - 1,2-dimethylbenzene



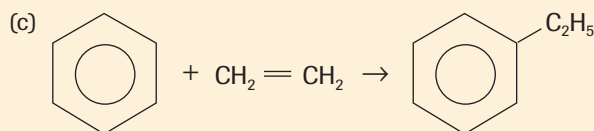
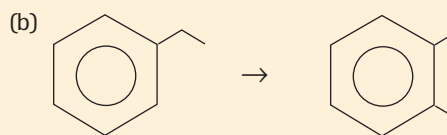
Figure 8
Isomers of dimethylbenzene, known as xylenes, are used as solvents.

- Write IUPAC names for the following aromatic hydrocarbons:



- Aromatics can also take part in various chemical refining reactions. For each of the following reactions, draw a structural formula equation where names are given and provide names where structures are given.

(a) propylbenzene $\rightarrow$ methylbenzene + ethene



- Classify each of the following hydrocarbons as aromatic or aliphatic.

- 2,3-dimethylhexane
- $\text{CH}_3\text{—CH}_2\text{—CH(C}_6\text{H}_5\text{)—CH}_3$
- 1,2-dimethylcyclohexane
- 4-methylpent-2-yne
- 1,3-dimethylbenzene
- 2-phenyl-3-hexene

- Classify each of the following hydrocarbons as saturated or unsaturated.

- $\text{C}_2\text{H}_4(\text{g})$
- $\text{CH}_3\text{—(CH}_2\text{)}_4\text{—CH}_3$
- $\text{C}_6\text{H}_5\text{CH}_3(\text{l})$
- $\text{C}_3\text{H}_4(\text{g})$
- $\text{CH}_3\text{—(CH}_2\text{)}_2\text{—CH}_3$
- $\text{C}_6\text{H}_6(\text{l})$

- Why is benzene not called cyclohex-1,3,5-triene, to communicate three double bonds in a hexagon?
- In Lab Exercise 9.B, you compared the boiling points of hexane, hex-1-ene, cyclohexane, cyclohexene, and benzene. Test the ability of the concept of London forces to explain the relative order of the boiling points of these C_6 hydrocarbons. Did the London-force concept or your understanding of it need to be revised to provide an acceptable explanation? (According to philosophers of science, in this question, you are testing the explanatory power of a scientific concept.)
- Even though the use of benzene as a solvent was banned in Canada several decades ago, people's exposure to benzene has not stopped. A Materials Safety Data Sheet (MSDS) is the source of chemical safety information. List some common sources of benzene exposure and identify some short-term and long-term health effects.

9.5 Crude Oil Refining



Figure 1
Pump jacks are found over oil wells in many parts of Alberta. This one is near Cochrane, Alberta.

Crude oil is pumped from the ground by thousands of pump jacks throughout Alberta (**Figure 1**). The crude oil then enters a pipeline through which it is shipped to an oil refinery. If the oil has to travel a long distance, pumping stations are situated along the way to assist the movement of the oil. Much of the oil in Alberta is exported to other provinces and other countries for refining. Some of the oil is refined in Alberta.

Crude oil throughout the world is classified on the basis of viscosity, hydrocarbon composition, and sulfur content. (Viscosity is a measure of how well a liquid pours: low-viscosity liquids pour like water, whereas high-viscosity liquids pour like molasses or liquid honey.) For example, light crude oil has a lower viscosity and requires less refining than heavy or high-viscosity crude oil. While some types of crude oil are best suited for gasoline production, other types of crude oil may be better suited for jet fuel, diesel fuel, home heating, motor oil, and asphalt end products (**Figure 2**). Most crude oil is separated into a variety of components that differ according to the percentage of each component obtained. This separation can involve both physical and chemical processes.

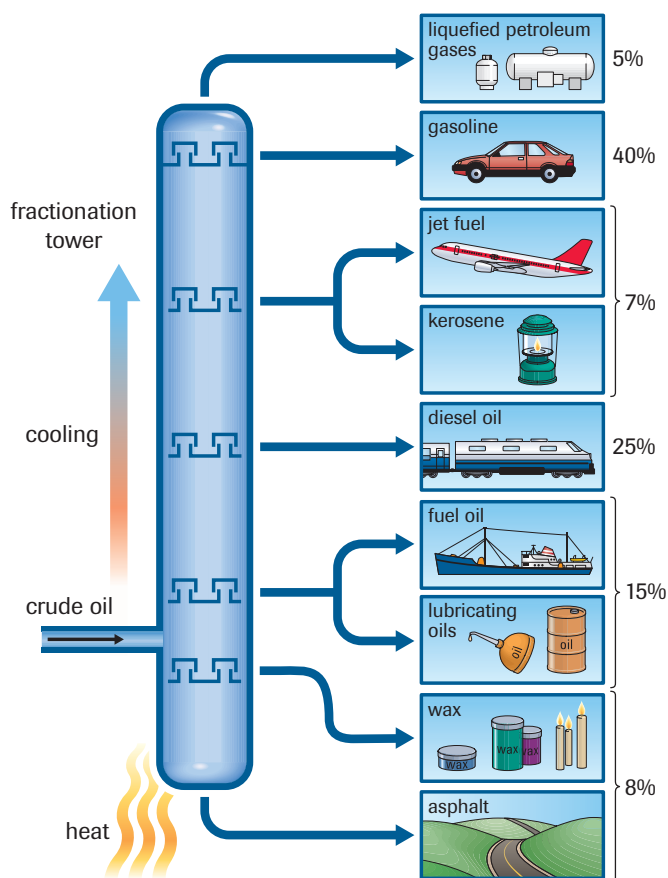


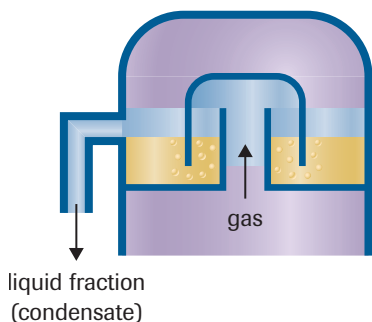
Figure 2
A fractional distillation (fractionation) tower contains trays positioned at various levels. Heated crude oil enters near the bottom of the tower. The bottom of the tower is kept hot, and the temperature gradually decreases toward the top of the tower. The concentration of components with lower boiling points increases from the bottom to the top of the tower. The percentage distributions shown vary with the type of crude oil and with seasonal demands.

Physical Processes in Oil Refining

Crude oil is a complex mixture of hundreds of thousands of compounds. Some of these compounds boil at temperatures as low as 20 °C. The least volatile components of crude oil, however, boil at temperatures above 400 °C. Chemical engineers take advantage of the differences in boiling points to physically separate the components. This technological process is called *fractional distillation*, or **fractionation**.

Any substance with a boiling point above 25 °C is a liquid or solid at SATP. Chemical engineers have found that, when crude oil is heated to 500 °C in the absence of air, most of its constituent compounds vaporize. The compounds with boiling points higher than 500 °C remain as mixtures called asphalts and tars. The vaporized components of the crude oil rise and gradually cool in a metal tower (**Figure 2**). The technological design is very ingenious: To get from one level to the next, the vapours have to force their way through the liquid in the next tray. Bubble caps, which were used in the past, illustrate the contact between liquid and vapour (**Figure 3**). Currently, valve trays, which are more efficient, are used in distillation columns. When the temperature of the liquids in the trays in the higher parts of the tower is below the boiling points of the vaporized compounds, the substances in the vapour begin to condense. Those substances with high boiling points condense in the lower, hotter trays of the tower, whereas those with lower boiling points condense in the cooler trays near the top of the tower. Side streams are withdrawn from various locations along the column. These various streams are called **fractions**. Some typical fractions and their properties are listed in **Table 1**.

Chemists have an explanation for the boiling points of these fractions. They have found that the fractions with the lowest boiling points generally contain the smallest molecules. Chemists explain that the low boiling points are due to small molecules,

**Figure 3**

The vaporized components are forced to bubble through the liquids condensed in each tray. Any gas with its condensation point (boiling point) greater than the temperature of the liquid in the tray will condense. The liquid in each tray continuously overflows into the draining tube and the liquid mixture is piped from the fractionation tower.

Table 1 Fractional Distillation of Crude Oil

Boiling point range of fraction (°C)	Number of carbon atoms per molecule	Fraction (intermediate product)	Products
below 30	1 to 5	gases; LPGs	gaseous fuels for cooking and for heating homes
30 to 90	5 to 6	naphthas	dry-cleaning solvents, naphtha gas, camping fuel
30 to 200	5 to 12	straight-run gasoline	automotive gasoline
175 to 275	12 to 16	kerosene	diesel, jet, and kerosene fuels; cracking stock* (raw materials for fuel and petro-chemical industries)
250 to 375	15 to 18	light gas or fuel oil	furnace oil; cracking stock
over 350	16 to 22	heavy gas oil	lubricating oils; cracking stock
over 400	18 and up	greases	lubricating greases; cracking stock
over 450	20 and up	paraffin waxes	candles, waxed paper, cosmetics, polishes; cracking stock
over 500	26 and up	unvaporized residues	asphalts and tars for roofing and paving

* Cracking stock is feedstock (raw material) that is, for example, hydrocracked to make smaller molecules that are more in demand; e.g., gasoline molecules.

which have fewer electrons and weaker London forces compared with large molecules. The fractions with higher boiling points are found to contain much larger molecules. Some typical fractions are shown in **Table 1**. Recall from Chapter 3 that London forces are also dependent on the shape of the molecules; that is, on whether the molecule is branched. Since these molecules are hydrocarbons, chemists explain that dipole–dipole and hydrogen bonding are not involved.

Other Physical Processes in Oil Refining

In addition to fractional distillation, there are several other physical processes that are used to treat fractions before and/or after chemical processing. 📌 Several of these physical processes are **solvent extractions**—a solvent is added to selectively dissolve and remove an impurity or to separate some useful products from a mixture. Dewaxing is a simple process of cooling a mixture to precipitate the larger wax fraction.

DID YOU KNOW?

Naphthas

Like all of the fractions listed in Table 1, naphtha is a mixture with varying composition (including aliphatic and aromatic hydrocarbons). The mixture depends on the source of the hydrocarbon (e.g., light or heavy crude, bitumen, or coal) or customer demand. Naphtha, for example, may be petroleum naphtha with more aliphatic character, or bitumen naphtha with more aromatic character. What defines it as naphtha is the boiling point range over which it is collected in the fractionator.

CAREER CONNECTION



Petroleum Engineer

Petroleum engineers apply their knowledge of chemistry to the discovery, recovery, and processing of oil and gas deposits.

Rob Manuel is a petroleum engineer. He combines his Western scientific world view with his Aboriginal world view (he grew up on the Upper Nicola Indian Band Reserve) to bring a “different way of thinking to the table.” Find out about the education petroleum engineers require for the kind of work they do.

www.science.nelson.com





INVESTIGATION 9.3 Introduction

Report Checklist

Fractional Distillation (Demonstration)

Fractional distillation is a process used commercially to separate components (fractions) of petroleum using boiling point differences.

Purpose

The purpose of this investigation is to use the concept and technique of fractional distillation to separate two hydrocarbon components from a liquid mixture.

Problem

What is the percent by volume of each of the two hydrocarbon components?

To perform this investigation, turn to page 402.

- | | | |
|----------------------------------|---|---|
| ☐ Purpose | ☐ Design | ☒ Analysis |
| ☐ Problem | ☐ Materials | ☐ Evaluation |
| ☐ Hypothesis | ☐ Procedure | |
| ☐ Prediction | ☒ Evidence | |

Design

A mixture of the two liquids is heated in a fractional distillation apparatus while the temperature is measured at regular intervals in a fume hood.

DID YOU KNOW?

Oil Recovery

The recovery of oil can be enhanced by the use, for example, of water or of carbon dioxide. Recent research has shown that carbon dioxide can be captured from large industries and transported by pipeline to oil wells. The recovery of the oil from underground increases from about 25% to about 40%. The carbon dioxide used in this application helps reduce emissions and helps meet Kyoto targets.

Practice

- State some similarities and differences between the operation of a fractionation tower and a laboratory-scale distillation apparatus.
- Why is crude oil heated in the absence of air in the fractionation tower?
 - Write chemical equations to represent the vaporization of pentane and of octane at the bottom of a fractionation tower.
 - Write chemical equations to represent the condensation of pentane and of octane in a bubble-cap tray of a fractionation tower.
 - Which of pentane and octane has a higher boiling point, and why?
 - Which of pentane and octane is removed in a higher bubble tray of the fractionation tower?
- Feedstock is raw or semi-processed material that is fed into a chemical process to produce a more valuable product. Cracking stock is feedstock that is cracked into smaller or more branched hydrocarbons. List the different fractions that are used as cracking stock. Suggest some reasons why so many fractions are used for this purpose.
- What percentage of petroleum is used as fuel? What is the major type of fuel that makes up this category?
- Straight-run gasoline is gasoline that comes straight from a crude-oil, fractional distillation tower. There are various kinds of crude oil, including light, heavy, and synthetic. Some kinds of oil provide a greater percentage of straight-run gasoline than others.
 - Describe the straight-run gasoline fraction compared to other crude oil fractions.
 - Write balanced chemical equations for the complete combustion of the pentane and octane components of straight-run gasoline while driving a hybrid (gasoline and electric) automobile.
- Crude oil is a solution of many, many hydrocarbons, including hydrocarbons that are solids, liquids, and gases as pure substances at SATP.
 - Explain how this mixture can be a solution.
 - Water is part of the mixture when extracting crude oil from oil wells. Use intermolecular forces concepts to explain why water would or would not be a solute in the crude oil solution.
- Use the information in this section to add to your collection of statements, pro and con, from a variety of perspectives on the resolution that the burning of fossil fuels should be reduced.

Chemical Processes in Oil Refining

The refining of crude oil can be divided into two main types of processes: physical processes, such as fractionation and solvent extraction, and chemical processes, such as cracking and reforming (Figure 4). These chemical processes are necessary because the fractional distillation of crude oil does not produce enough of the hydrocarbons that are in demand (particularly the gasoline fraction) and produces too much of the heavier fractions. Compared to gasoline and diesel, there is limited market demand for fuel oil, lubricating oils, greases, and waxes. Notice that all of these fractions (Table 1, page 387) contain larger molecules than those typically found in gasoline (C_5 to C_{12}). ➦

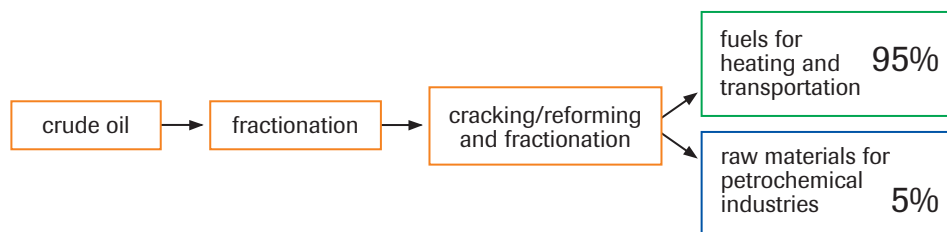


Figure 4

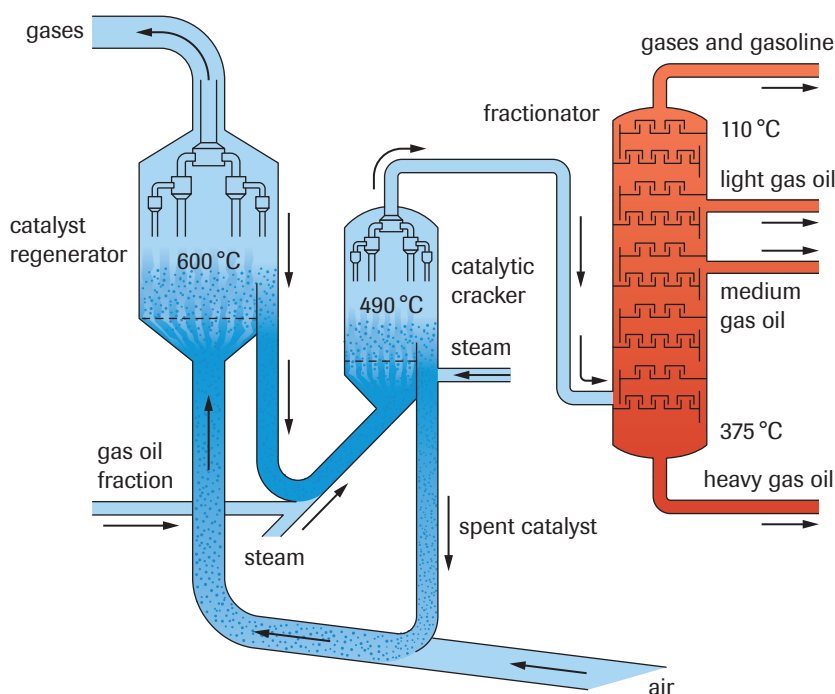
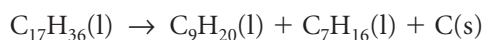
Only 5% of the original mass of crude oil is used as starting chemicals (called feedstock) in the manufacture of solvents, greases, plastics, synthetic fibres, and pharmaceuticals.

www.science.nelson.com



Cracking

Cracking is a chemical process in which larger molecules are broken down with heat and/or catalysts to produce smaller molecules. In the early 1900s, cracking was accomplished using only high temperatures and pressures in a process called *thermal cracking*. This process is fairly effective, but is messy and wasteful because it produces large quantities of solid coke (carbon). Thermal cracking is still used today, but to a limited extent. By 1937, basic research and technological development produced a new improved cracking technique called *catalytic cracking* (Figure 5). This process breaks apart larger molecules, but the presence of a catalyst, along with less severe reaction conditions, produces more desirable fractions and less residual materials such as tar, asphalt, and coke. (You will learn more about the uses of catalysts in chemical processes in Chapter 12.) A typical reaction equation might be



CAREER CONNECTION



The Petroleum Industry

The Petroleum Human Resources Council of Canada has been set up to handle the huge demand for employees in the areas of exploration, development, production, service industries, pipeline transmission, gas processing, and the mining, extracting, and upgrading of heavy oil and bitumen. Find out more about the Petroleum HR Council, the seven human resource issues it has identified, and the strategies it has developed to address any one of these issues. If you were interested in working in this field, how might the Petroleum HR Council's work benefit you?

www.science.nelson.com



Figure 5

For catalytic cracking, the gas oil fraction, for example, enters the central vessel, is catalytically cracked, and then fractionated again in the column on the right. The catalyst is recycled into the vessel on the left. The catalyst is regenerated when the coke is burned off of it in the left vessel.

DID YOU KNOW?

Ammolite Gems and Ammonite Fossils

Ammolite (**Figure 6(a)**) is one of only three organic gemstones, besides pearl and amber, but contains traces of up to a dozen metals. The highly supported hypothesis is that ammolite comes from the shells of ammonites—squid-like creatures that lived about 75 Ma ago in the Bearpaw Sea that ran north to south through the middle of Alberta (**Figure 6(b)**). Aboriginal peoples, ranchers, and prospectors have found ammolite along the banks of the St. Mary River, south of Lethbridge, Alberta. Ammolite is the only uniquely Canadian gem, and has been mined and refined in Alberta since the 1980s.

Ammolite is also known as aapoak (Blackfoot for small, crawling stone) and buffalo stone (also named by the Blackfoot of southern Alberta). The latter name comes from the Blackfoot legend about a princess who found an ammolite gemstone that brought prosperity (in the form of a buffalo herd) back to the Blackfoot. Since then, the Blackfoot have regarded ammolite as a sign of prosperity.

(a)



(b)

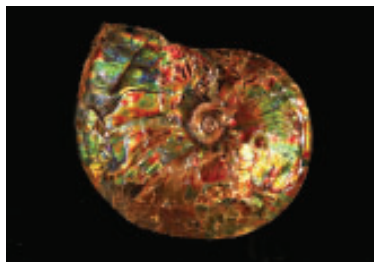
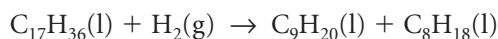


Figure 6

(a) An ammolite gem and (b) an ammonite fossil

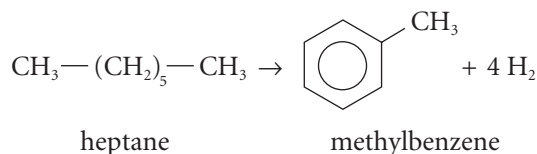
The history of oil refining is a story of continuous technological development to meet societal needs for various petroleum products, in particular, gasoline. In 1960, another improvement, called hydrocracking, helped meet this demand. **Hydrocracking** is a combination of catalytic cracking and hydrogenation and is used for heavier feedstocks, particularly those containing complex aromatic compounds. During the hydrogenation process, no coke (carbon) is produced. A simplified hydrocracking reaction equation would be



Catalytic Reforming and Alkylation

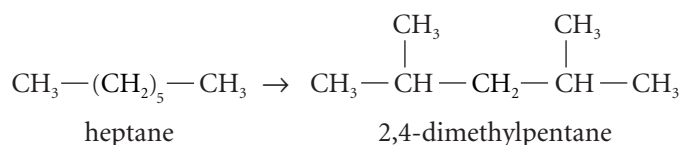
Cracking reactions are like decomposition reactions because the main objective is to break larger molecules into smaller ones. Both the fractionation process and the cracking process produce large quantities of light fractions such as gases and naphthas (**Table 1**, page 387), as well as molecules whose structures are not suitable for our needs. For example, there might be too few branches on the molecules to produce a sufficiently high-quality gasoline. The chemical process of reforming and alkylation rearranges the bonding in molecules to improve the quality of the gasoline.

Catalytic reforming is the chemical process involved in converting molecules in a naphtha (gasoline) fraction into aromatic gasoline molecules. These aromatic molecules have better burning properties than the original aliphatic (non-aromatic) molecules. For example, heptane does not burn well in internal combustion (car) motors. If the heptane is converted into methylbenzene, the gasoline burns better in car motors. All reforming is now done with the use of catalysts to increase the rate of the reaction, and is, therefore, often called catalytic reforming. Hydrogen, a by-product of catalytic reforming, is usually recycled in other processes, such as hydrocracking.



Alkylation

Another way of improving the quality of gasoline is to increase the branching of the molecules in a process called *alkylation*. This process is also called isomerization because it converts a molecule into a branched isomer. For example, heptane can be converted into 2,4-dimethylpentane, a molecule that burns better in an internal combustion motor.



WEB Activity

Canadian Achievers—Karl Chuang

Karl Chuang studied chemical engineering at the University of Alberta in the 1970s. Today, he is a top distillation expert in Canada and one of the best in the world. He has developed distillation technologies that are used in refineries around the world.

What are Dr. Chuang's current research interests?

www.science.nelson.com



SUMMARY

Gasoline and diesel fuel are high-demand crude oil fractions. More of each of these fractions can be made by cracking heavier fractions. Also, molecules that burn better in internal combustion motors can be made by chemical processes (e.g., catalytic reforming and alkylation) controlled by chemical engineers.

Catalytic cracking: larger molecules $\rightarrow$ smaller molecules + carbon

Hydrocracking: larger molecule + hydrogen $\rightarrow$ smaller molecules

Catalytic reforming: aliphatic molecule $\rightarrow$ aromatic molecule + hydrogen

Alkylation (isomerization): aliphatic molecule $\rightarrow$ more branched isomer

Practice

- Why are chemical processes necessary in oil refining, in addition to the physical process of fractionation?
- Write a condensed structural formula equation for each of the following catalytic cracking reactions. Assume that unbranched alkanes are produced, in addition to carbon (coke). There are many possible product combinations. Predict one combination.
 - $\text{CH}_3-(\text{CH}_2)_{16}-\text{CH}_3 \rightarrow$
 - decane $\rightarrow$
 - $$\begin{array}{c}
 \text{H} & \text{H} & \text{H} \\
 | & | & | \\
 \text{H}-\text{C}-\text{C}-\text{C}-\text{H} \\
 | & | & | \\
 \text{H} & \text{H} & \text{H}
 \end{array}
 \rightarrow$$
- Compare hydrocracking and catalytic reforming. In what way are they complementary?
- High-quality gasoline requires chains of C_5 to C_{12} molecules, branching within the molecules, and some aromatic molecules. For each of these three requirements, identify the physical and/or chemical process that accomplishes the requirement.
- Since crude oil contains many alkanes, unwanted hydrocracking reactions are common in the first stage of oil refining during fractionation. The hydrogen is a product of thermal cracking. For each of the following word equations representing hydrocracking reactions, write a balanced condensed structural formula equation:
 - hexane + hydrogen $\rightarrow$ ethane + butane
 - 2-methylpentane + hydrogen $\rightarrow$ propane + propane
 - 2,2-dimethylbutane + hydrogen $\rightarrow$ ethane + methylpropane
- After initial fractional distillation, catalytic reforming and alkylation reactions increase the yield of desirable products, such as compounds whose molecules have aromatic character and more branches. Complete each of the following equations. Draw condensed structural formulas when IUPAC names are given, and write IUPAC names when condensed structural formulas are given.
 - $$\begin{array}{c}
 \text{CH}_3 - \text{CH}_2 - \text{CH}_3 + \text{CH}_3 - \text{CH}_2 - \text{CH}_2 - \text{CH}_3 \rightarrow \\
 \text{CH}_3 - \text{C}(\text{CH}_3)_2 - \text{CH}_2 - \text{CH}(\text{CH}_3) - \text{CH}_3
 \end{array}$$
 - octane $\rightarrow$ 1,3-dimethylbenzene + hydrogen
 - $\text{CH}_3 - (\text{CH}_2)_3 - \text{CH}_3 \rightarrow \text{C}_3\text{H}_5(\text{C}_2\text{H}_5) + \text{H}_2$
 - decane $\rightarrow$ 3-ethyl-2-methylheptane

DID YOU KNOW?

Transportation Fuels

About 50% of crude oil processed in Canadian refineries is used as transportation fuels—gasoline, diesel fuel, jet fuel, and fuel oil for ships and locomotives. The demand keeps increasing, although, for example, the decreasing demand for fuel oil for heating homes (in Eastern Canada) has allowed more of the fuel-oil supply to be used as a transportation fuel.

DID YOU KNOW?

Oil Sands Discovery

In 1719, a Cree named Wa-pa-su took a sample of Athabasca oil sands to the Hudson Bay Post in Fort Churchill. Aboriginal peoples used the tarry substance, mixed with tree sap, to waterproof their canoes and other items.

Extension

14. Benzene and other aromatic hydrocarbons have a low H:C ratio (close to 1:1). Chemical engineers have invented two processes to increase this ratio to about 2:1.
 - (a) Explain how the 1:1 hydrogen-to-carbon ratio is derived for aromatics.
 - (b) What classes of hydrocarbons have H:C ratios close to 2:1?
 - (c) Describe how hydrocracking works to improve the H:C ratio of aromatics from approximately 1:1 to approximately 2:1.
15. For economic and efficiency reasons, crude oil refining technologies have moved from thermal cracking to catalytic cracking. Both catalytic cracking and hydrocracking employ catalysis. Chemical engineers who are designing modern refineries are increasingly moving toward hydrocracking over straight catalytic cracking. What is an advantage of hydrocracking over catalytic cracking?

Case Study

Octane Number

Hydrocracking, alkylation, and catalytic reforming reactions produce not only more gasoline, but also convert low-grade gasoline into higher-grade gasoline. At gas stations, you see the grades displayed on the gas pumps, for example, as Regular and Super or as a specific number, such as 88 and 98. The numbers, 88 and 98, represent the octane rating (number) of the gasoline.

Low-octane gasoline, with long straight-chain molecules, burns quickly. Fuel is supposed to ignite in the cylinder as a result of a spark. The spark is timed to ignite the fuel when the piston is close to the top of its “up stroke” (see **Figure 7**). Sometimes the mixture auto-ignites as a result of the pressure in the cylinder, rather than burning when the spark is produced. If the fuel ignites earlier, high-performance vehicle engines lose some of their efficiency. They sometimes produce a knocking or pinging sound. High-performance gasoline engines require high-octane fuel, which contains more branched-chained and aromatic hydrocarbons. Higher-octane gasoline resists spontaneous (high-pressure, no-spark) auto-ignition of excess fuel. The engine runs more smoothly, and is less likely to be damaged or lose efficiency.

Russell Marker, a chemist, assigned 2,2,4-trimethylpentane (an isomer of octane) an octane number of 100, and heptane (a straight-chain alkane) an octane number of zero. These chemicals were chosen for comparison due to their similar boiling points and enthalpies of vaporization (**Table 2**).

In addition to using high-octane gasoline to reduce knocking in high-performance engines, an additive (octane booster) can be used. From the 1920s until the 1970s, the most common additive was tetraethyl lead, $\text{Pb}(\text{C}_2\text{H}_5)_4$ (l). Because lead deactivated the catalysts in the catalytic converters installed in cars starting in 1972, tetraethyl lead was removed from gasoline by the 1990s.

Several ingredients have replaced the tetraethyl lead, such as dibromoethene (ethylene dibromide, EDB), dichloroethene (ethylene chloride, EDC), and 2-methyl-2-methoxypropane (methyl tertiary butyl ether, MTBE). Each substitute has had its own problems.

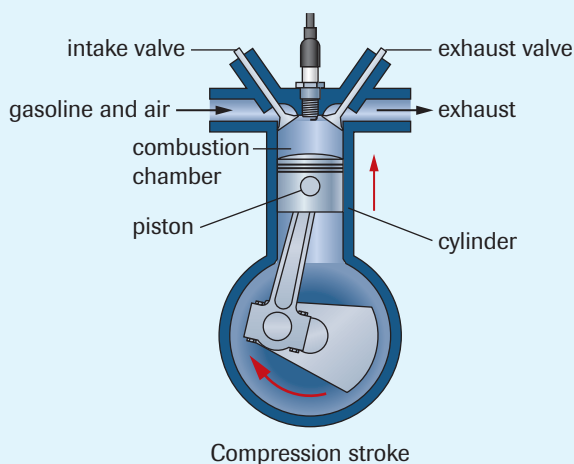


Figure 7

Engine knock in an internal combustion engine is caused by auto-ignition of excess fuel occurring between carefully timed sparks.

Table 2 Octane Rating Reference Scale

Chemical	Boiling point (°C)	Octane rating
heptane $\text{CH}_3 - (\text{CH}_2)_5 - \text{CH}_3$	98.4	0
2,2,4-trimethylpentane $ \begin{array}{c} \text{CH}_3 \qquad \qquad \text{CH}_3 \\ \qquad \qquad \quad \\ \text{CH}_3 - \text{C} - \text{CH}_2 - \text{CH} - \text{CH}_3 \\ \\ \text{CH}_3 \end{array} $	99.3	100

Case Study Questions

- As they relate to octane rating of gasoline, why are alkylation and catalytic reforming reactions carried out?
- Predict the reaction products in a word equation, and then write a structural formula equation for each of the following gasoline reactions. Recall that complete combustion involves a reaction with oxygen to produce the most common oxides.
 - octane + oxygen $\rightarrow$
 - 2,2,4-trimethylpentane + oxygen $\rightarrow$
 - heptane + oxygen $\rightarrow$
 - methylbenzene (toluene) + oxygen $\rightarrow$
- Knocking occurs when compression ignites fuel during the power stroke that did not ignite initially from the spark provided by the spark plug (**Figure 7**). Write line structural formulas for the following hydrocarbons in the internal combustion engine.
 - 1,3-dimethylbenzene enters the cylinder through the intake port of the cylinder.
 - 2,3-dimethylbutane is ignited by a spark from the spark plug at the top of the compression stroke.
 - Hexane is ignited by heat and high pressure before completion of the compression stroke.
 - Decane (an excess/unreacted hydrocarbon) exits through the exhaust port of the cylinder.

Sulfur in Gasoline

Many organic compounds incorporate sulfur in their molecules. Sulfur in gasoline is a pollution problem. When the gasoline is burned, sulfur emissions reduce air quality and can also decrease the pH of rain, resulting in acid deposition. **Table 3** presents typical emissions found in the exhaust of a well-tuned automobile with a catalytic converter.

Besides contributing to the problem of acid deposition, sulfur dioxide causes problems even before leaving the exhaust pipe of an automobile. Sulfur dioxide and sulfur atoms in unburned fuel tend to reduce the effectiveness of the catalytic converter. (You will learn more about the catalytic converter in Chapter 12.) This reduced effectiveness increases the quantity of other pollutants, such as carbon monoxide and nitrogen oxides, that make their way through the exhaust system and into the air.

Research indicates that refined gasoline has a typical average sulfur content of 340 ppm, although the range is from 30 ppm to 1000 ppm. Some jurisdictions have legislated a sulfur content as low as 30 ppm.

The technology that scientists and engineers have created to reduce the sulfur content in gasoline is a process called hydrogenation or hydrotreating. Hydrogen gas (likely obtained by catalytic reforming of crude oil fractions) reacts with sulfur atoms in gasoline molecules to produce hydrogen sulfide gas. The $\text{H}_2\text{S}(\text{g})$ is then converted to sulfur and water in a Claus converter (**Figure 8**).

Table 3 Typical Gasoline Automobile Exhaust

Gas	Volume (%)
carbon dioxide	9
oxygen	4
hydrogen	2
carbon monoxide	4–9
hydrocarbons	< 0.2
aldehydes	0.004
nitrogen oxides	0.05–0.4
sulfur dioxide	0.006
ammonia	0.0006
nitrogen, etc.	$\approx 75^*$

* The approximate 75% includes, for example, water vapour that condenses into a vapour trail on a cold winter day.

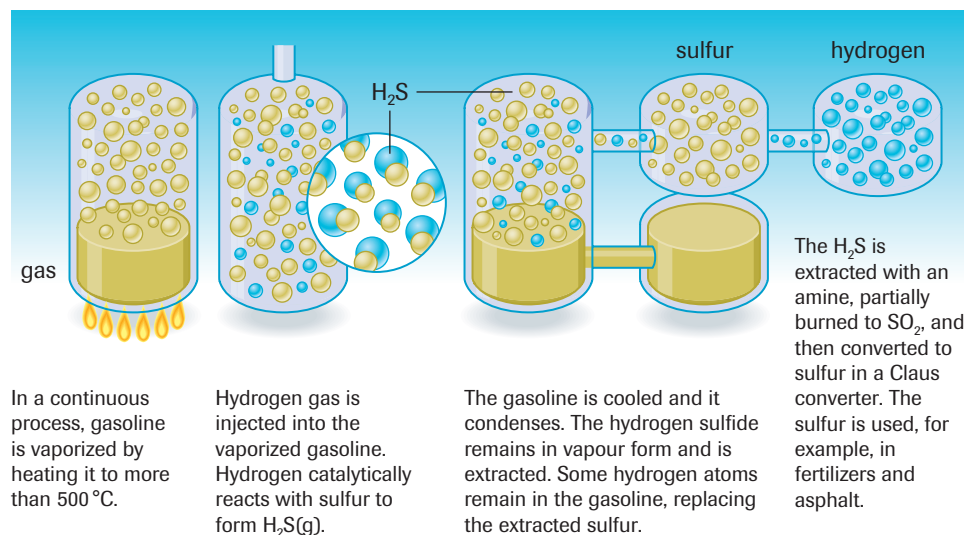


Figure 8

To achieve the federally mandated goal of sulfur reduction in gasoline, suppliers needed to invest in new or additional desulfurization equipment, another step in the refining process. Refineries in Alberta have upgraded to reduce sulfur content in their products. Alberta oil refineries include

- Ft. Saskatchewan (Shell)
- Edmonton (PetroCanada)
- Edmonton (Imperial Oil)

DID YOU KNOW?

Sulfur Compounds

There are many organic compounds that contain sulfur. They have traditionally been identified by the use of suffixes:

thiol indicates $R-S-H$

thio represents $R=S$

sulfide communicates $R-S-R$
(R represents a hydrocarbon chain.)

Practice

16. There are many possible sulfur-bearing organic compounds in gasoline. Write a condensed structural formula equation to communicate the hydrogenation (hydrotreating) of sulfur to hydrogen sulfide for the following sulfur compounds. (You are not required to name organic compounds of sulfur.) For example, octanethiol: $CH_3-(CH_2)_7-SH(l) + H_2(g) \rightarrow H_2S(g) + CH_3-(CH_2)_6-CH_3(l)$
- (a) $S=CH-CH_2-CH(C_6H_5)-CH_3$
(b) methylphenylsulfide, $CH_3SC_6H_5$
17. Researchers have predicted that the price of gasoline must increase by 1–3 ¢/L in order to finance the further refining of gasoline to decrease the sulfur content to 30 ppm.
- (a) Would you be willing to pay the extra price? Why or why not?
(b) What alternatives do we have to using sulfur-containing gasoline for fueling our transportation needs?



INVESTIGATION 9.4 Introduction

Bitumen from Oil Sands

In 1920, Canadian Karl Clark invented the hot water and caustic soda, $NaOH(s)$, recovery process for extracting bitumen from oil sands. In 1923, Clark and associates at the Alberta Research Council set up a pilot project in the basement of the power plant at the University of Alberta. After decades of work, the first economically feasible world-scale plant for the extraction of bitumen from oil sands was opened in 1967 near Fort McMurray by what is now Suncor Energy.

Recent advances in bitumen extraction have called into question the need for caustic soda. This investigation involves testing the old process.

Purpose

The purpose of this investigation is to test the need for caustic soda in the extraction of bitumen from oil sands.

To perform this investigation, turn to page 403.

Report Checklist

- | | | |
|----------------------------------|---|---|
| ☐ Purpose | ☐ Design | ☒ Analysis |
| ☐ Problem | ☐ Materials | ☒ Evaluation (3) |
| ☐ Hypothesis | ☐ Procedure | |
| ☐ Prediction | ☒ Evidence | |

Problem

What is the percentage, by mass, of bitumen in an oil sands sample?

Design

The volume of caustic soda solution added to a hot water and oil sands mixture is systematically varied. Each research group uses a different volume of caustic soda and reports the percentage mass of bitumen obtained to the other groups.



INVESTIGATION 9.5 Introduction

Solvent Extraction (Demonstration)

Solvent extraction of bitumen from oil sands has significant importance for the development of the oil sands chemical industry in Alberta. Some in-situ bitumen extraction processes use a solvent. Most, if not all, of the surface mining bitumen extractions use a solvent to assist with bitumen extraction during the hot-water extraction process. This investigation asks you to predict which of water, propan-2-ol (an alcohol), or naphtha (a distillation fraction) is the best solvent for bitumen.

Purpose

The purpose of this investigation is to test solubility theory to predict which solvents can be used to dissolve bitumen.

To perform this investigation, turn to page 404.

Report Checklist

- | | | |
|---|--|---|
| ☐ Purpose | ☒ Design | ☒ Analysis |
| ☐ Problem | ☒ Materials | ☒ Evaluation (1, 2, 3) |
| ☐ Hypothesis | ☒ Procedure | |
| ☒ Prediction | ☒ Evidence | |

Problem 1

Which of water, propan-2-ol, or naphtha is the best solvent for extracting bitumen from oil sands?

Problem 2

Which of water, propan-2-ol, or naphtha is the best solvent for extracting bitumen from water?

Case Study

The Athabasca Oil Sands

World technology at present is utterly dependent on energy from burning fuels derived from petroleum. We know that oil resources are finite, and that oil production must, inevitably at some point, reach a peak and then decline. In the continental United States (the world's biggest oil consumer), production peaked in 1970. The world's production peak is predicted at various times by different specialists in this area, but few predict it later than the mid-21st century, and some argue that it is already here. Alberta has a huge and growing interest in this area because Alberta's oil reserves are very large.

The special case in Alberta is that the reserves are mostly not liquid crude oil, but rather bitumen—a tarry residue coating the sand grains of the immense Athabasca and other oil sand deposits (**Figure 9**). Mining oil sand and then separating bitumen from the sand (**Figure 10**) is a huge operation, involving equipment and processes on a massive scale (**Figure 11**).



Figure 9
Bitumen permeates this sample of “oil sand.”



Figure 10
Chemical engineering is required to extract bitumen from oil sands (left) and then convert bitumen (right) into synthetic crude oil.



Bitumen Extraction

As indicated in Investigation 9.4, Karl Clark used controlled experiments to develop the caustic hot water process for bitumen extraction from oil sands. He and others found that oil sand is typically 84% sand, 12% bitumen, and 4% water. Further research has shown that the sand particles are surrounded by a thin layer of water and then a thicker layer of bitumen (**Figure 12**).

Experience shows that if the oil sand dries out, the hot water process for extracting bitumen from the sand does not work: The water layer disappears and the bitumen sticks very tightly to the sand.

A current technology is to have the initial separation occur in a hydrotransport pipeline that simultaneously carries the oil sands and caustic hot water, and separates the bitumen from the sand. At the plant, the mixture is physically separated by density in a large conical vessel into bitumen froth, water, and sand. The bitumen froth, created by blowing air into the mixture, floats to the top and is skimmed off.



Figure 11
The complex processes in this refinery eventually produce a valuable “synthetic” crude oil product.

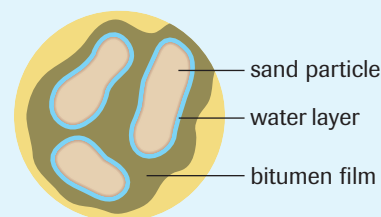


Figure 12
Close examination of oil sand shows a sand particle surrounded by water and bitumen.

Many technological advances for bitumen extraction have occurred through research over the last couple of decades, and many more creative advances for bitumen extraction and upgrading are likely to occur in the next couple of decades.

The transforming of bitumen into useful liquid synthetic crude oil, however, is where the chemistry of organic reactions comes into play, in a reaction system that has great importance for Alberta, Canada, and the world. Bitumen is about 20% alkanes and cycloalkanes in the form of very complex branched chains; and about 80% aromatic compounds with multiple rings, forming many complex structures, from rather small to extremely large molecular sizes. Converting the bitumen into a useful product begins either with a process called coking or with hydrocracking. Both of these processes increase the hydrogen-to-carbon (H/C) ratio of bitumen. Coking removes carbon and hydrocracking adds hydrogen.

Bitumen Upgrading: Coking

Coking involves spraying bitumen onto a bed of hot (500 °C) coke particles. Coke is a material like charcoal, with a very high carbon content. Coking vaporizes the smaller molecular substances in bitumen, and causes thermal cracking in the larger molecular substances. (No catalyst is present, so the cracking is caused by high-temperature collisions.) The cracking produces many new substances that then vaporize. The process also causes some of the substances in the original bitumen to convert to solid, granular coke. When the hot vapour leaves the coking vessel and is cooled, much of it condenses to liquid that can be separated into fractions, just as is done with crude oil.

Bitumen Upgrading: Hydrocracking

Molecules in a sample of bitumen have a molar mass of 500–800 g/mol and an H/C ratio of less than one. Similar to coking, hydrocracking breaks the large aromatic molecules in bitumen into smaller aromatic and aliphatic molecules (increasing the H/C ratio). The aromatic character of bitumen results in a greater aromatic character to synthetic crude oil compared to conventional crude oil. Hydrocracking uses a catalyst to increase the rate of the cracking reaction at a lower temperature. As the name, hydrocracking, suggests, hydrogen is also a reactant—to increase the H/C ratio, convert unsaturated hydrocarbons to saturated hydrocarbons, and to remove, for example, nitrogen and sulfur impurities.

Bitumen Upgrading: Hydrotreating

Hydrotreating is the process of causing reactions of the organic substances in partially upgraded (cracked) bitumen with hydrogen, at high temperature and pressure. The reactions remove impurities, particularly nitrogen and sulfur, which cause problems with the uses for synthetic crude oil. The hydrogenation reactions also convert any double or triple carbon-carbon bonds in the liquids to single bonds, to make the molecules more stable (less reactive).

Case Study Questions

- Use solubility theory to explain
 - the natural existence of oil sands as separate layers of bitumen and then water next to the sand
 - the reason for choosing water as the liquid for extracting bitumen from oil sands
 - the difficulty of separating bitumen from sand when oil sand is left standing to dry out
 - the need for a hydrocarbon solvent for extracting bitumen from oil sand that has been dried by our sun
- What is the H/C ratio of the following compounds?
 - naphthalene in bitumen (**Figure 13**)
 - methylbenzene in gasoline
 - heptane in naphtha (camping fuel)

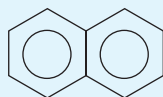


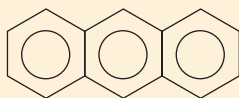
Figure 13

The molecular structure of naphthalene, a small molecule in bitumen

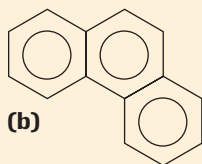
- During coking, a naphthalene, $C_{10}H_8(l)$, molecule (**Figure 13**) in a bitumen sample is thermally cracked into a hexane molecule and a but-2-ene molecule as products.
 - Write and balance an equation for this reaction, using any structural formula to represent each of the substances involved.
 - What is the H/C ratio for each of naphthalene, hexane, and but-2-ene?
- Consider the hydrotreating of this organic substance: $H_2NCH_2CSCH_2COOH + \text{___ } H_2(g) \rightarrow$
 - Complete a balanced chemical equation to produce the most common hydrogen compounds of N, S, and O and a saturated hydrocarbon.
 - Why is more hydrotreating needed after coking than after hydrocracking?
- For each of the following reactions of one mole of reactant, predict the product, including its structural formula and name, and state the chemical amount (in moles) of hydrogen required for complete reaction.
 - $CH_2CHCHCH_2 + \text{___ } H_2(g) \rightarrow$
 - $HCCCH_2CH_2C_6H_5 + \text{___ } H_2(g) \rightarrow$
- The oil sands are a huge source of oil for Alberta, Canada, and the world. The development of this resource will cost billions of dollars and cause environmental damage. Why are we developing the oil sands? Answer, pro and con, from a variety of perspectives and add these statements to your Exploration issue concerning the resolution that the burning of fossil fuels for heat and transportation should be significantly reduced.
- Fly through the whole process, from the initial mining of the oil sands to the final products, in this video. Prepare a flowchart to describe the oil sands process.

Section 9.5 Questions

- What physical property of hydrocarbons is used for fractionation?
 - What chemical theory explains the difference in the physical property used for fractionation?
- Using Table 1 (page 387), identify all products that you have used and classify them as essential, useful, convenient, or a luxury.
- Why does crude oil have to be chemically processed, in addition to being fractionated?
 - How would our technologies and/or our society be different without the invention of these processes?
- The conceptual understanding of any phenomenon in science usually starts with the creation of a classification system. Classify and write condensed structural formula equations for each of the following organic reactions. Catalysts are involved in all reactions other than combustion.
 - ethane $\rightarrow$ ethene + hydrogen
 - hexane $\rightarrow$ benzene + hydrogen
 - 4,4-dimethylpent-2-yne + hydrogen $\rightarrow$
propene + methylpropane
 - methylbenzene + oxygen $\rightarrow$
 - nonane $\rightarrow$ 1-ethyl-3-methylbenzene + hydrogen
 - $\text{CH}_3(\text{CH}_2)_{16}\text{CH}_3$ + hydrogen $\rightarrow$
nonane + octane + methane
- Predict a possible structural equation for the following reaction classes and reactants. There are many correct answers.
 - combustion of decane
 - hydrocracking of decane
 - catalytic reforming of decane
- What chemical processes are used for the upgrading of bitumen?
- What is the chemical difference between
 - bitumen and crude oil?
 - synthetic and conventional crude oil?
- Evidence gathered in the laboratory by analytical chemists indicates that the molecules in bitumen have a hydrogen-to-carbon ratio of 1:1 or less. The interpretation placed on this evidence is that the molecules are composed of multiple benzene rings (**Figure 14**).



(a)



(b)

Figure 14

Anthracene **(a)** and phenanthrene **(b)** are a couple of the smaller aromatic compounds found in bitumen and coal.

- Write the molecular formula for each molecule in Figure 14.
 - What is the H/C ratio for each of these aromatic compounds?
 - Propose a chemical reaction equation for the hydrocracking of anthracene.
- In terms of molecules, compare low-octane and high-octane gasoline. What technological processes did engineers invent to convert low-octane gasoline into high-octane gasoline?
 - Only 10–25% of the crude oil in an oil well is initially recovered using current technology. 95% of the recovered oil is burned, and only 5% is used to make useful products, such as pharmaceuticals and plastics. Some people argue that it is morally wrong for our generation to be burning this valuable chemical resource rather than giving future generations the opportunity to extract more of it using more advanced technology. Use this information (and other information from this section) to add pro and con perspective statements to the Evidence section of your Exploration (STS issue) report from page 357.

Extension

- Compare the following processes:
 - thermal cracking and catalytic cracking
 - hydrocracking and catalytic reforming
 - hydrocracking and hydrotreating
 - catalytic reforming and alkylation
- In addition to alkanes, cracking reactions may also involve alkenes, alkynes, and aromatics. For each of the following reactions, draw a structural formula equation. Include all reactants and products.
 - but-1-ene $\rightarrow$ ethyne + ethane
 - 3-methylheptane $\rightarrow$ but-2-ene + butane
 - 3-methylheptane $\rightarrow$ propene + 2-methylbut-1-ene + hydrogen
 - propylbenzene $\rightarrow$ benzene + propene
- For each of the following alkylation reactions in gasoline refining (octane boosting), draw a structural formula or write the IUPAC name for each reactant and product.
 - 2-methylpent-1-ene $\rightarrow$ 2,3-dimethylbut-1-ene
 -



9.6 Complete and Incomplete Combustion Reactions

When organic compounds undergo combustion reactions (burning), they release large quantities of energy (mainly heat and light) and chemical products, including carbon dioxide, carbon monoxide, particles of solid carbon (soot), and water vapour. In general, organic compounds may undergo two forms of combustion: complete combustion and incomplete combustion. Both of these reactions are exothermic.

DID YOU KNOW?

Natural Gas Consumption

Chemical industries consume about half of the natural gas in Alberta. The natural gas serves as an energy source or as a feedstock (raw material) for the industries.

Complete Combustion

In complete combustion, a hydrocarbon (fuel) reacts with oxygen to produce carbon dioxide and water vapour as the only chemical products. For example, the complete combustion of 2,2,4-trimethylpentane, a component of gasoline, may be communicated in the form of a word equation, a balanced chemical equation, and a structural formula equation as follows:

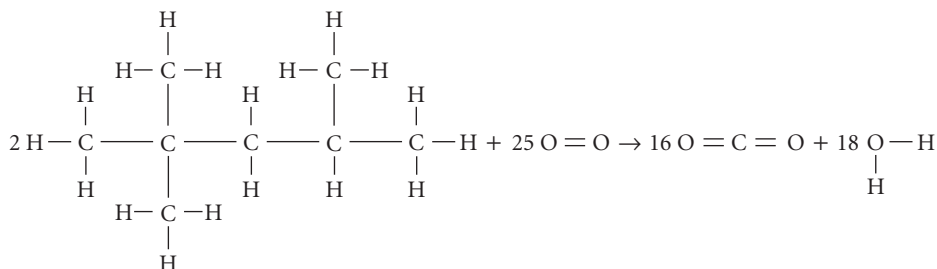
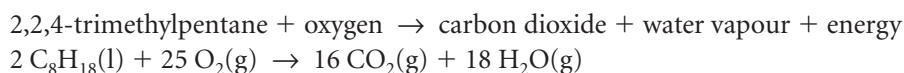
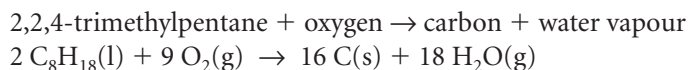
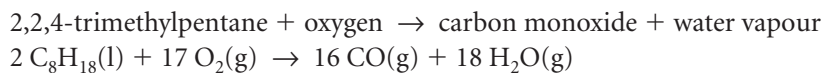


Figure 1

A yellow flame is evidence of incomplete combustion—in a candle, camp fire, laboratory burner, barbecue, or furnace. Soot and/or poisonous carbon monoxide gas are likely products, as evidenced by soot deposits on objects that are passed through the flame.

Incomplete Combustion

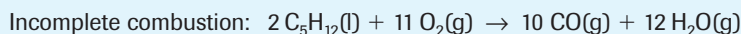
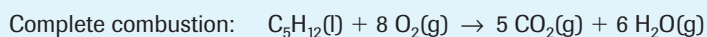
Unlike complete combustion, the incomplete combustion of an organic compound may include reactions that produce carbon monoxide and soot or any combination of carbon dioxide, carbon monoxide, and carbon (soot), in addition to water and energy (**Figure 1**). Using 2,2,4-trimethylpentane as an example, we can communicate two possible incomplete combustion reactions in the form of word equations and balanced chemical equations as follows:



COMMUNICATION example

For dimethylpropane, write balanced chemical equations for complete combustion, and for incomplete combustion to produce carbon monoxide.

Solution



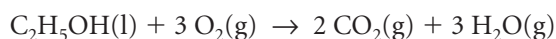
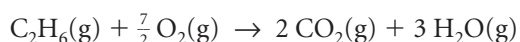
Practice

1. Write chemical and structural formula equations for complete and one possible incomplete combustion reaction of butane (in a lighter).
2. When automobiles burn gasoline, combustion is incomplete. Complete combustion produces carbon dioxide, a greenhouse gas. Incomplete combustion produces carbon monoxide, a toxic gas that becomes part of the airborne “chemical soup.” Write a balanced chemical equation to represent one possible incomplete combustion of each of the following gasoline components to carbon monoxide, carbon dioxide, and water vapour.
(a) 3-methylhexane (b) benzene (c) cyclohexane

Evidence from combustion studies indicates that all three types of combustion reactions occur simultaneously when an organic compound is burned, albeit not in equal proportions. Comparing the equations for complete and incomplete combustion of 2,2,4-trimethylpentane, you will notice that the fuel-to-oxygen mole ratio decreases from a high of 2:25 in complete combustion, to 2:17 in the reaction producing carbon monoxide, to 2:9 in the reaction producing soot. Thus, increasing the amount of oxygen available during combustion may increase the proportion of complete combustion reactions that occur. Even an excess of oxygen does not guarantee that only complete combustion will take place. The larger the excess of oxygen available during combustion, however, the smaller the amount of carbon monoxide and soot that is produced.

Carbon monoxide is a toxic gas that can reach dangerous levels in a confined area (such as in a house, a car, and even in a city). Reducing carbon monoxide emissions from oil and gas furnaces, gas stoves, and vehicles helps keep atmospheric concentrations of carbon monoxide low. In some places, alcohol is added to gasoline to help reduce carbon monoxide emissions. When added to gasoline, alcohols are often called *oxygenerators* because they provide additional oxygen to the combustion reaction. Oxygenerators make the combustion more complete, as evidenced by the reduced quantity of carbon monoxide and soot in the exhaust of automobiles that have been tested. In fact, some jurisdictions legislate the percentage of oxygenator that must be included in gasoline.

The following two equations allow you to compare the combustion of ethane and ethanol. Note the smaller chemical amount of oxygen required to burn ethanol:



DID YOU KNOW?

Ethanol in Gasoline

In the 1920s and 1930s, cars could be converted to run on gasoline, ethanol (from corn), or a 25% blend of ethanol with gasoline. In 2002, about 620 000 m³ of corn were used to produce ethanol for blending with gasoline in hundreds of gas stations in Canada. The importance of ethanol has returned! It takes approximately 1.5 L of ethanol to deliver the same energy as 1.0 L of regular gasoline. The percentage of carbon monoxide emissions from burning ethanol or ethanol-blended gasoline, however, is significantly reduced. Despite this drawback, some provinces now have legislation that calls for mandatory blending of ethanol in gasoline.



INVESTIGATION 9.6 Introduction

Complete and Incomplete Combustion

Complete combustion has several benefits over incomplete combustion. Even complete combustion can create problems for the environment, however. In this investigation, you have an opportunity to start a research program (a major experimental design) on improving combustion. This is an open entry investigation. You create it and then possibly carry it out.

Purpose

The purpose of this investigation is to create a research program to improve combustion of, for example, candle wax.

Report Checklist

- | | | |
|----------------------------------|--|--|
| ☐ Purpose | ☒ Design | ☒ Analysis |
| ☐ Problem | ☒ Materials | ☒ Evaluation (1, 3) |
| ☐ Hypothesis | ☒ Procedure | |
| ☐ Prediction | ☒ Evidence | |

Problem

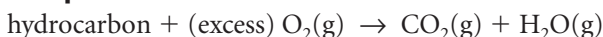
How can the combustion of a hydrocarbon be improved?

To perform this investigation, turn to page 404.

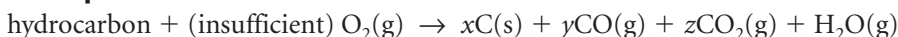
SUMMARY

Complete and Incomplete Combustion

Complete Combustion



Incomplete Combustion



(The ratio of $x:y:z$ largely depends on the proportion of oxygen available.)

Section 9.6 Questions

1. The primary reaction of the components of natural gas is combustion with oxygen from the air. The primary product of these combustion reactions is energy. List three chemical by-products of this energy-producing reaction.
2. Write molecular and condensed structural formula equations for the combustion of pentane (in winter gasoline). Assume complete combustion.
3. Evaluate, with reasoning, the statement: "Fossil fuels must contain significant quantities of nitrogen because nitrogen oxides are found in the exhaust of cars and trucks."
4. Combustion is not always complete, usually because of an insufficient supply of oxygen. Write a hypothesis, including a chemical equation, to explain the following events.
(a) When ethyne (acetylene) is burned in air, black soot appears.
(b) Deaths have occurred when charcoal briquettes (assume pure carbon) are burned inside a tent to keep campers warm on a cold night.
(c) Deaths have occurred when people fall asleep in the back seat of a car that has a leaky muffler.
5. Gasoline is not a mixture of pure hydrocarbons. Some of the hydrocarbon molecules are contaminated with nitrogen, sulfur, and oxygen atoms. Air pollutants, such as nitrogen dioxide and sulfur dioxide, are produced from the combustion of these molecules. Write unbalanced chemical equations to represent the complete combustion of
(a) $\text{C}_6\text{H}_5\text{NO}(\text{l})$ (b) $\text{C}_4\text{H}_8\text{S}(\text{l})$ (c) $\text{NHC}_3\text{H}_4\text{S}(\text{l})$
6. Canadians are among the highest producers of greenhouse gases in the world; for example, the average Albertan produces five tonnes per annum of greenhouse gases. The One-Tonne Challenge (OTC) to each Canadian is to reduce his or her greenhouse gas production by the equivalent of one tonne of carbon dioxide per year. Write pro and/or con statements from at least four perspectives concerning the resolution that GHGs should be reduced.

7. Use the information in this section to add to your list of pro and con perspective statements regarding your resolution on reducing fossil fuel consumption.

Extension

8. Evidence-based reasoning and scientific concept-based reasoning are goals of science and of science education. There are many examples of claims that gather a following even though they are based on anecdotal evidence and concepts that have not gained acceptance by the scientific community. Use the links provided to start an investigation into claims of spontaneous human combustion. What is your evaluation, based on the evidence and on accepted scientific concepts?
9. Chemists communicate their research through peer-reviewed (refereed) journals. (See Appendix B.4.) Other chemists who do research on the same topic search for and read the abstract to see if they want to read the full research report. Read the abstract provided by the link below. What fuel was added to the natural gas and what effect did it have on the carbon dioxide emission?

www.science.nelson.com



www.science.nelson.com



INVESTIGATION 9.1

Classifying Fossil Fuels

Alberta has many different fossil fuels. Samples of fossil fuels can be described and classified in terms of their physical properties of colour, transparency, viscosity, and density. In this investigation, the focus is on density.

Purpose

The purpose of this investigation is to use the known properties of fossil fuels to analyze the provided samples.

Problem

What are the classes of the fossil fuel samples provided?

Design

Equal-volume samples of fossil fuels are provided in sealed containers of equal mass. The mass of each sample, including the container, is determined. The fossil fuel samples are classified based upon their densities.

Report Checklist

- | | | |
|----------------------------------|--|--|
| ☐ Purpose | ☐ Design | ☒ Analysis |
| ☐ Problem | ☐ Materials | ☒ Evaluation (1, 3) |
| ☐ Hypothesis | ☒ Procedure | |
| ☐ Prediction | ☒ Evidence | |

Materials

lab apron eye protection
equal volume samples, labelled A to G, of
heavy oil natural gas
light oil medium oil
coalbed methane bitumen
coal

Table 1 Densities of Fossil Fuels

Fossil fuel class	Density (g/cm ³)
methane	0.0007165
light crude oil	0.800–0.850
medium crude oil	0.875–0.900
heavy crude oil	0.935–1.000
bitumen	>1.000–1.075
coal	1.3–>2.0

INVESTIGATION 9.2

Structures and Properties of Isomers

Molecular models are visual representations of molecules that help us to understand some of the properties and structures of molecules. In addition to building models, this investigation asks you to consult references to obtain data gathered by chemists over many years of laboratory work.

Purpose

The purpose of this investigation is to use models and a reference, respectively, to examine the structures and physical properties of some isomers of unsaturated hydrocarbons.

Problem

What are the structures and physical properties of the isomers of C₄H₈ and C₄H₆?

Design

Structures of possible isomers are determined by means of a molecular model kit. Once each structure is named, the boiling

Report Checklist

- | | | |
|----------------------------------|---|---|
| ☐ Purpose | ☐ Design | ☒ Analysis |
| ☐ Problem | ☐ Materials | ☒ Evaluation (3) |
| ☐ Hypothesis | ☐ Procedure | |
| ☐ Prediction | ☒ Evidence | |

and melting points are obtained from a reference such as the *CRC Handbook of Chemistry and Physics* or *The Merck Index*.

www.science.nelson.com



Materials

molecular model kits chemical reference

Procedure

1. Use the required “atoms” to make a model of C₄H₈.
2. Draw a structural formula of the model and write the IUPAC name for the structure.
3. Rearrange bonds to produce models for all other isomers of C₄H₈, including cyclic structures. Draw structural formulas and write the IUPAC name for each structure before disassembling the models.



INVESTIGATION 9.2 *continued*

- If you construct a model that contains a double C–C bond, test the restricted rotation of groups about the bond axis and the bond length.
- Repeat steps 1 to 4 for C_4H_6 .
- In a reference, find the melting point and the boiling point of each of the compounds you identified.



INVESTIGATION 9.3

Fractional Distillation (Demonstration)

Fractional distillation is a process used commercially to separate molecular components of petroleum using boiling point differences. The same technique can be used to separate components of most liquid mixtures, provided a significant boiling point difference exists. In this demonstration, the vapours of the boiling mixture rise into a fractionating column, where initially they all condense and fall back into a flask. When the temperature in the column rises sufficiently, vapours of the component with the lower boiling point pass through the column and enter a condenser, which cools and condenses the component back to a liquid for collection. The component with the higher boiling point still condenses in the fractionating column, which separates the two liquids.

Purpose

The purpose of this investigation is to use the concept and technique of fractional distillation to separate two hydrocarbon components from a liquid mixture.

Problem

What is the percent by volume of each of the two hydrocarbon components?

Design

A mixture of the two liquids is heated in a fractional distillation apparatus while the temperature is measured at regular intervals in a fume hood.

Materials

lab apron
eye protection
round-bottom distillation flask
electric heating mantle
2 small collecting flasks
stopwatch
fume hood

thermometer or temperature probe to fit column stopper
pentane, $C_5H_{12}(l)$
2-methylpropan-2-ol, $CH_3C(CH_3)_2OH$
fractionating column
stand and clamp

Report Checklist

- | | | |
|----------------------------------|---|---|
| ☐ Purpose | ☐ Design | ☒ Analysis |
| ☐ Problem | ☐ Materials | ☐ Evaluation |
| ☐ Hypothesis | ☐ Procedure | |
| ☐ Prediction | ☒ Evidence | |

50 mL graduated cylinder
large 400–600 mL beaker
condenser with tubing and fittings

Procedure

- Obtain a 50 mL sample of the mixture of unknown composition.
- Heat the flask slowly, taking the vapour temperature at regular 30 s intervals.
- After most of the pentane has boiled off, when the column temperature rises noticeably, change collection flasks at the outflow of the condenser (**Figure 1**).
- Measure the volume of pentane collected.
- As soon as most of the alcohol has boiled off, remove the heating mantle.
- Dispose of the organic chemicals into an organic waste container.

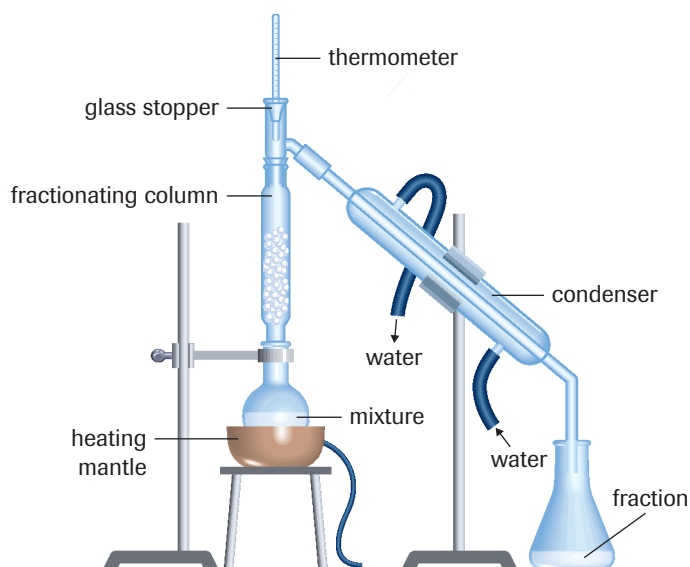


Figure 1

A fractional distillation apparatus

**INVESTIGATION 9.4****Bitumen from Oil Sands**

In 1920, Canadian Karl Clark invented the hot water and caustic soda, NaOH(s), recovery process for extracting bitumen from oil sands. In 1923, Clark and associates at the Alberta Research Council set up a pilot project in the basement of the power plant at the University of Alberta. After decades of work, the first economically feasible world-scale plant for the extraction of bitumen from oil sands was opened in 1967 near Fort McMurray by what is now Suncor Energy.

Surface mining of oil sands allows for over 90% recovery of the bitumen. This percentage compares very favourably with in-situ oil sands at 25-75%, conventional heavy oil at less than 20%, and conventional light oil at about 30%. Fortunately for the environment, over 80% of the oil sands will have to be mined in-situ rather than from a surface mine. Unfortunately, the recovery rate of in-situ operations is significantly lower using current technologies.

Recent advances in bitumen extraction have called into question the need for caustic soda. This investigation involves testing the effects of using various amounts of caustic soda (sodium hydroxide).

Purpose

The purpose of this investigation is to test the need for caustic soda in the extraction of bitumen from oil sands.

Problem

What is the percentage, by mass, of bitumen in an oil sands sample?

Design

The volume of caustic soda solution added to a hot water and oil sands mixture is systematically varied. Each research group uses a different volume of caustic soda and reports the percentage mass of bitumen obtained to the other groups.

Materials

eye protection
lab apron
ring stand
wire gauze
250 mL beaker
400 mL beaker
ring clamp
laboratory burner or hot plate
beaker tongs

Report Checklist

- | | | |
|----------------------------------|---|--|
| ☐ Purpose | ☐ Design | ☒ Analysis |
| ☐ Problem | ☐ Materials | ☒ Evaluation (1, 3) |
| ☐ Hypothesis | ☐ Procedure | |
| ☐ Prediction | ☒ Evidence | |

dropper bottle of 1.0 mol/L NaOH(aq)
small disposable plastic spoon
100 g of oil sands
laboratory balance
disposable clear plastic container
paper towel



Sodium hydroxide is corrosive. Avoid skin and eye contact.

Procedure

1. Add about 250 mL of tap water to the 400 mL beaker.
2. Add 0, 4, 8, and 12 (as assigned to your research group) drops of 1.0 mol/L sodium hydroxide solution to the water.
3. Heat the water to boiling.
4. Place the disposable plastic container into a paper-towel-lined 250 mL beaker (or equivalent).
5. Add a measured mass of oil sands to the disposable container and set the container on a paper towel.
6. Use the beaker tongs to pour water onto the oil sands to make a slurry.
7. Use the plastic spoon to stir the slurry for about 5 min.
8. Use the beaker tongs again to add about 100 mL more hot water to nearly fill the container.
9. Allow the contents of the container to settle.
10. Measure the mass of a double layer of paper towel.
11. Use the plastic spoon to remove the bitumen from the container onto a double layer of paper towel.
12. Dry and measure the mass of the bitumen plus paper towel.

INVESTIGATION 9.5

Solvent Extraction (Demonstration)

Solvent extraction of bitumen from oil sands has significant importance for the development of the oil sands chemical industry in Alberta. Some in-situ bitumen extraction processes use a solvent. Most, if not all, of the surface mining bitumen extractions use a solvent to assist with bitumen extraction during the hot-water extraction process. This investigation asks you to predict which of water, propan-2-ol (an alcohol), or naphtha (a distillation fraction) is the best solvent for bitumen.

Purpose

The purpose of this investigation is to test solubility theory to predict which solvents can be used to dissolve bitumen.

Report Checklist

- | | | |
|---|--|---|
| ☐ Purpose | ☒ Design | ☒ Analysis |
| ☐ Problem | ☒ Materials | ☒ Evaluation (1, 2, 3) |
| ☐ Hypothesis | ☒ Procedure | |
| ☒ Prediction | ☒ Evidence | |

Problem 1

Which of water, propan-2-ol, or naphtha is the best solvent for extracting bitumen from oil sands?

Problem 2

Which of water, propan-2-ol, or naphtha is the best solvent for extracting bitumen from water?

INVESTIGATION 9.6

Complete and Incomplete Combustion

Complete combustion has several benefits over incomplete combustion. Even complete combustion can create problems for the environment, however. In this investigation, you have an opportunity to start a research program (a major experimental design) on improving combustion. This is an open entry investigation. You create it and then possibly carry it out.

Report Checklist

- | | | |
|----------------------------------|--|--|
| ☐ Purpose | ☒ Design | ☒ Analysis |
| ☐ Problem | ☒ Materials | ☒ Evaluation (1, 3) |
| ☐ Hypothesis | ☒ Procedure | |
| ☐ Prediction | ☒ Evidence | |

Purpose

The purpose of this investigation is to create a research program to improve the combustion of, for example, candle wax.

Problem

How can the combustion of a hydrocarbon be improved?

Outcomes

Knowledge

- define organic compounds, recognizing inorganic exceptions (9.1)
- identify and describe organic compounds in everyday life, as well as their origins and applications (all sections)
- name and draw structures for saturated and unsaturated aliphatic and aromatic hydrocarbons (9.2 to 9.6)
- classify organic compounds from their structural formulas (9.2 to 9.5)
- define and use the concept of structural isomerism and relate to properties of isomers (9.2 to 9.4)
- compare boiling points and solubility of organic compounds (9.2 to 9.4)
- describe fractional distillation and solvent extraction (9.1, 9.2, 9.3, 9.5)
- define, provide examples of, predict products, and write and interpret balanced equations for combustion reactions (9.1, 9.2, 9.5, 9.6)
- describe major reactions for producing energy and economically important compounds from fossil fuels (all sections)

STS

- illustrate how science and technology are developed to meet societal needs and expand human capabilities (all sections)
- describe interactions of science, technology, and society (all sections)
- illustrate how science and technology have both intended and unintended consequences (9.1, 9.2, 9.5, 9.6)

Skills

- initiating and planning: describe procedures for safe handling, storing, and disposal of materials used in the laboratory, with reference to WHMIS and consumer product labelling information (9.5)
- performing and recording: separate a mixture of organic compounds based on boiling point differences (9.5); build molecular models depicting the structures of selected organic and inorganic compounds (9.3)
- analyzing and interpreting: follow IUPAC guidelines for naming and formulas and by compiling evidence to compare the properties of structural isomers (all sections); compile and organize data to compare the properties of structural isomers (9.3); investigate sources of greenhouse gases, that is, methane, carbon dioxide, water, and dinitrogen oxide (nitrous oxide) and the issue of climate change (all sections)
- communication and teamwork: work cooperatively in addressing problems and apply skills and conventions of science in communicating information and ideas and in assessing results by preparing reports on topics related to organic chemistry (all sections)

Key Terms



9.1

organic chemistry
hydrocarbon
refining

9.2

alkane
homologous series
saturated hydrocarbon
structural isomer
alkyl branch
cycloalkane

9.3

unsaturated compound
hydrogenation
alkene

alkyne

cycloalkene
cracking
aliphatic hydrocarbon

9.4

aromatic
phenyl group

9.5

fractionation
fraction
solvent extraction
hydrocracking
catalytic reforming

► MAKE a summary

- Create a concept map starting with “Fossil Fuels” in the centre of a page. Include all of the Key Terms, Key STS, and Key Skills, as well as any other information you think may be useful in studying for a test on this chapter.
- Refer back to your answers to the Starting Points questions at the beginning of this chapter. How has your thinking changed?

► Go To

www.science.nelson.com



The following components are available on the Nelson Web site. Follow the links for *Nelson Chemistry Alberta 20–30*.

- an interactive Self Quiz for Chapter 9
- additional Diploma Exam-style Review questions
- Illustrated Glossary
- additional IB-related material

There is more information on the Web site wherever you see the Go icon in this chapter.

Many of these questions are in the style of the Diploma Exam. You will find guidance for writing Diploma Exams in Appendix H. Exam study tips and test-taking suggestions are on the Nelson Web site. Science Directing Words used in Diploma Exams are in bold type.

www.science.nelson.com



DO NOT WRITE IN THIS TEXTBOOK.

Part 1

- Organic chemistry is defined as the study of
 - all carbon compounds
 - all carbon compounds except cyanide
 - all carbon compounds except oxides and ionic compounds
 - carbon-containing compounds produced by living organisms
- Chemists have developed classification systems for the compounds they study. The empirical classification of hydrocarbons is based on
 - physical properties only
 - chemical properties only
 - physical and chemical properties
 - physical and chemical properties and empirically determined molecular formulas
- Hydrocarbons that contain a benzene ring in their molecules are called
 - aromatics
 - alkanes
 - alkenes
 - alkynes

Use this information to answer questions 4 to 6.

- hex-1-ene
- hex-1-yne
- 1,2-dimethylbenzene
- hex-2-ene
- 2-methylpent-2-ene
- benzene
- cyclohexane
- cyclohexene
- methylbenzene

4. In numerical order, the alkenes are

NR _____

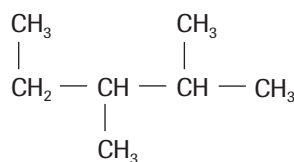
5. In numerical order, the aromatics are

NR _____

6. In numerical order, the isomers of C_6H_{12} are

NR _____

7. The IUPAC name for the following hydrocarbon is

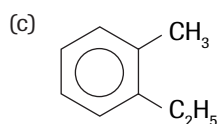
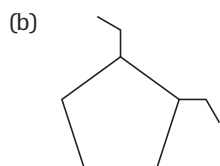
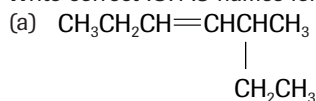


- 3,4-dimethylpentane
 - 2,3-dimethylpentane
 - 1,2,3-trimethylbutane
 - 4,5,6-trimethylbutane
- Differences in boiling points are the basis of
 - catalytic cracking
 - solvent extraction
 - catalytic reforming
 - fractional distillation
 - The natural gas used by consumers to heat their homes contains mostly
 - methane
 - ethane
 - propane
 - butane
 - For a related series of hydrocarbons, such as unbranched alkanes, a property that decreases as molar mass increases is
 - boiling point
 - melting point
 - volatility
 - viscosity
 - The change in boiling point of alkanes with increasing molar mass is primarily due to increasing
 - London forces
 - dipole-dipole forces
 - covalent bonds
 - hydrogen bonds
 - Separating the components of natural gas can involve all of the following processes *except*
 - fractionator
 - Claus converter
 - condenser
 - amine scrubber
 - The technology of cracking and reforming hydrocarbons was developed primarily to meet the societal demand for
 - asphalt for paving highways
 - lubricating oils for machines
 - gasoline for automobiles
 - propane for home heating
 - The chemical reaction that produces coke is
 - combustion
 - catalytic reforming
 - catalytic cracking
 - alkylation

15. Identify the missing product in the following catalytic cracking reaction: $C_{17}H_{36}(l) \rightarrow C_8H_{18}(l) + \text{_____} + C(s)$
- $CH_3C(CH_3)_2(CH_2)_3CH_3(l)$
 - $C_8H_{16}(l)$
 - $C_8H_{18}(l)$
 - $C_6H_5(CH_3)_2(l)$

Part 2

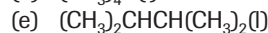
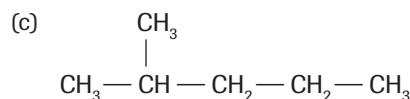
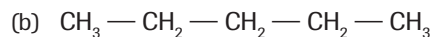
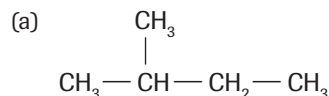
16. Write correct IUPAC names for the following structures:



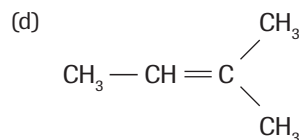
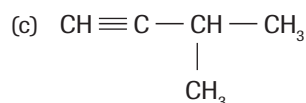
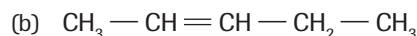
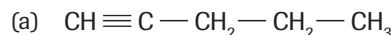
17. Draw a structural formula for each of the following compounds, and write the IUPAC name for each:
- ethylene
 - propylene
 - acetylene
 - toluene, the toxic solvent used in many glues
 - the three isomers of xylene (dimethylbenzene), used in the synthesis of other organic compounds such as dyes
18. Using your knowledge of elements and compounds, **explain** why carbon forms more compounds than all other elements combined.
19. List some examples of carbon-containing compounds that are not classified as organic. What do these compounds have in common?
20. State the name and formula of the simplest member of each of the four hydrocarbon families and include one important use of each.
21. Can a molecular formula for an aliphatic hydrocarbon be used to predict the specific family to which it belongs? **Explain**, using examples and noting limitations.
22. **Compare** the physical processes of distillation and solvent extraction.
23. Draw a line structural formula for each hydrocarbon.
- 2-methylnonane
 - methylcyclopentane
 - hex-3-yne
 - 1,2,4-trimethylbenzene
 - 4-propyloctane
 - 2-phenylpropane
 - 3-methylpent-2-ene

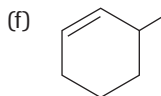
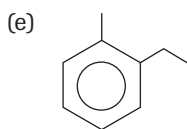
- 1,4-diethylbenzene
- 5-ethyl-2-methylhept-2-ene
- 4-methylpent-2-yne

24. Classify each hydrocarbon in question 23 into its family of hydrocarbons and **identify** which ones are saturated and which ones are unsaturated.
25. Draw structural formulas and write the IUPAC names for all the isomers of C_4H_8 .
26. In addition to alkanes, cracking reactions may also involve alkenes, alkynes, and aromatics. For each of the following reactions, draw a condensed structural formula equation. (You may draw a line structural formula for benzene.) Include all reactants and products.
- but-1-ene $\rightarrow$ ethyne + ethane
 - 3-methylheptane $\rightarrow$ but-2-ene + butane
 - 3-methylheptane $\rightarrow$
propene + 2-methylbut-1-ene + hydrogen
 - propylbenzene $\rightarrow$ methylbenzene + ethene
27. Classify the reaction type and write condensed structural formula (except for benzene) equations for the following organic reactions.
- ethane $\rightarrow$ ethene + hydrogen
 - but-2-ene + hydrogen $\rightarrow$ butane
 - 4,4-dimethylpent-2-yne + hydrogen $\rightarrow$
propene + methylpropane
 - methylbenzene + (excess) oxygen $\rightarrow$
 - decane $\rightarrow$ 2,2,4-trimethylheptane
 - octane $\rightarrow$ 1,3-dimethylbenzene
 - nonane $\rightarrow$ propane + pentane + carbon
28. Camping fuel is composed of alkanes with five or six carbon atoms per molecule. Name the following hydrocarbons found in this light naphtha fuel.



29. Write IUPAC names for the following hydrocarbons.





30. Coal is the most abundant fossil fuel in Alberta. The main use of coal in Alberta is to burn it to produce steam for driving turbines for turning electrical generators.
- If bituminous coal has an empirical (simplest ratio) formula of $C_9H_6O(s)$, **predict** a balanced chemical equation for the complete combustion of this coal.
 - The sulfur and nitrogen content of coal from Alberta is relatively low, which puts Alberta coal in demand in Canada and beyond. If a coal molecule has a molecular formula of $C_{100}H_{40}O_{10}N_2S(s)$, **predict** a balanced chemical equation for the complete combustion of this molecule.
31. The safe storage and handling of hydrocarbon fuels requires knowledge of their boiling points. The trends in boiling points within a hydrocarbon family make it possible to predict boiling points that are unknown. The purpose of this activity is to **identify** the trend in the boiling points for each family, and then use the trend to **predict** the boiling point of the next member of the series. Complete the Prediction, Analysis, and Evaluation (2, 3) of the investigation report.

Problem

What are the boiling points of hexane, hex-1-ene, and hex-1-yne?

Design

For three families (classes) of aliphatic hydrocarbons, the boiling points are plotted versus the number of carbon atoms per molecule. The graphs are extrapolated to predict the boiling point of the next member of each family. The predictions are evaluated by looking up the measured values in the *CRC Handbook of Chemistry and Physics*.

Evidence

See **Table 1** below.

32. Copy and complete **Table 2**.
33. For each of the following compounds, write its structural formula, and state its origin and a technological application.
- methane
 - ethene
 - ethyne
 - 2,2,4-trimethylpentane
 - 1,2-dimethylbenzene
34. Draw condensed structural formulas for and name the non-cyclic structural isomers of C_5H_{10} .

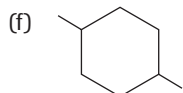
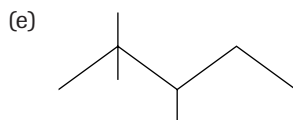
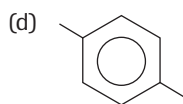
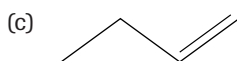
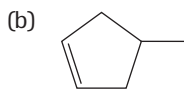
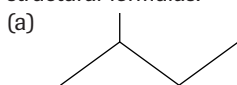
Table 1 Boiling Points of Aliphatic Hydrocarbons

Alkanes	Boiling point (°C)	Alkenes	Boiling point (°C)	Alkynes	Boiling point (°C)
ethane	−89	ethene	−104	ethyne	−84
propane	−42	propene	−47	propyne	−23
butane	−0.5	but-1-ene	−6.3	but-1-yne	8.1
pentane	36	pent-1-ene	30	pent-1-yne	40

Table 2 Some Important Hydrocarbons

IUPAC name	Condensed structural formula	Family/Class	Common use
	$CH_3 - C \equiv C - H$	alkynes	cutting/welding torch
	$CH_2 = CH_2$		petrochemical feedstock
propene			making plastics
methylpropane			butane lighters
2,3,3-trimethylpentane			gasoline
heptane		alkane	early anesthetic
methylbenzene			solvent

35. Write the IUPAC name of each of the following line structural formulas.



36. Complete the Design, Materials, and Procedure for the following investigation report.

Purpose

The purpose of this investigation is to use the properties of organic and inorganic chemicals to identify unknown chemicals.

Problem

Which of the chemicals provided is organic and which is inorganic?

37. Solvent extraction is used in chemical research and in the chemical industry to separate chemical components of a mixture. Researchers have found solvents that work best in specific situations. **Explain** the effectiveness of the solvent in each of the following processes.
- Naphtha is used to extract bitumen from a water, sand, and bitumen mixture.
 - Toluene (methylbenzene) is used to separate asphaltene (large aromatic molecules) from bitumen.
 - Water does not dissolve bitumen but is used to extract it from oil sands.
38. **Outline** the major processes used in the refining of crude oil. Your response should include
- some details of the physical and chemical changes at each stage of the process
 - chemical reaction equations to illustrate some of the chemical changes
 - a consideration of the impact of crude oil refining from several perspectives
39. Mining and oil development, due to their extractive nature, inevitably leave an environmental footprint, even before drilling occurs. For example, in its search for oil in the Edmonton area, Anadarko Petroleum has tested seismic lines near the Kehewin Cree people's reserve. Despite the assertion by Anadarko officials that the band will be consulted before drilling, some of the Aboriginal residents say the search itself may ruin traditional hunting grounds. Research this issue or another similar dispute from the perspective of the energy company, a local Aboriginal band, and an environmentalist. On what specific issues do these groups agree and disagree?

www.science.nelson.com



Extension

40. Some natural gas is sold without the hydrocarbon components being fractionated.
- Write a balanced chemical equation for the burning of natural gas containing the smallest four alkanes (see Table 1, page 363). Include a realistic mole ratio of the hydrocarbons in the balanced chemical equation.
 - Why is it that more and more of the natural gas being burned is nearly pure methane, even though it is expensive to remove the other components?
 - Why do some importers, such as the U.S., insist that the natural gas *not* be fractionated?
 - At one time in the past, the second-largest hydrocarbon component of natural gas that was most difficult to remove was not removed. Identify the component, and speculate as to why it was not removed and why the situation has changed.
41. Do a literature/media/Internet search for information on methane trapped in the Arctic ice of Canada. Present your findings in an innovative manner.
42. Quite often in the media, you hear or read stories about “proven oil reserves.” The most quoted source of this information is the U.S. Department of Energy. What is meant by the term “proven oil reserves”? Does the Middle East really have most of the oil in the world? What influence do politics and science have in determining oil reserves? Are the media giving a true picture of the world's oil reserves? Investigate these questions and present your findings, with illustrations and graphs, in a short article suitable for publication in a daily newspaper or on a Web page.

www.science.nelson.com



43. Cracking and reforming of crude oil are very complex chemical processes. Read about catalytic reforming and then list some of the other kinds of processes involved, such as polymerization.

www.science.nelson.com



44. In 1992, the International Institute for Sustainable Development (IISD) published the report *Our Responsibility to the Seventh Generation*. This report highlights the value of Indigenous knowledge and contributions to sustainable development. The report includes, for example, the quotation “We cannot simply think of our survival; each new generation is responsible to ensure the survival of the seventh generation.”
- What is the definition of sustainable development provided in this report?
 - In the Overview of the report starting on page 7, what are the one or two most prominent perspectives presented in the first three chapters? (See Appendix D.1.)

www.science.nelson.com

